ENERGY USE IN THE U.S. STEEL INDUSTRY: AN HISTORICAL PERSPECTIVE AND FUTURE OPPORTUNITIES

September 2000

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Steel Industry Consultant
Mason, Ohio

prepared under contract to
Energetics, Inc.
Columbia, MD

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The U.S. steel industry has taken enormous strides over the past decades to reduce its energy consumption; since the end of World War II, the industry has reduced its energy intensity (energy use per shipped ton) by 60 percent. Between 1990 and 1998 alone, intensity has dropped from 20 to 18 million Btu (MBtu) per ton. This figure is projected to decrease to 15 MBtu/ton by 2010 with an asymptotic trend towards 14 MBtu/ton.

Domestic shipments are projected to flatten out over the next decade to around 105 million tons which means that total energy consumption will also decrease. Historically, the steel industry has accounted for about 6 percent of U.S. energy consumption. Today, that figure is less than 2 percent and will decrease further to 1.5 percent by 2010.

The primary causes for the decrease in energy consumption since WWII are:

C The use of pellets in the blast furnace and the application of new technology in the ironmaking process to further reduce fuel rates per net ton of hot metal (NTHM).

C The total replacement of the open hearth process by basic oxygen and electric furnaces.

C The almost total replacement of ingot casting by continuous casting (which improved yield dramatically and thus reduced the tons of raw steel required per ton of shipments).

C The growth of the electric furnace sector of the industry at the expense of hot metal-based processes (which has also stimulated scrap recycling so that about 55 percent of “new” steel is now melted from scrap steel).

This report focuses on the concept of good practices (i.e., those that are sustainable and can use today's technology). If all the industry could operate on this basis, the additional savings per ton could total 2 MBtu. As further restructuring occurs and the swing from hot metal-based to electric furnace-based production continues, the average consumption will approach the good practice energy per ton. Further savings will accrue through new technology, particularly in the areas of reduced blast furnace fuel rates and reheating efficiency, both of which relate to large tonnages of material.

Currently, 48 million tons of carbon equivalent (CE) units are emitted for every 105 million tons of shipments (the projected average level of shipments over the next decade). This report suggests that CE emissions will likely decline to 43 million tons by 2010. Extrapolating back to 1990 and assuming 105 million tons of shipments rather than the actual 85 million tons for that year, yields estimated 1990 emissions of 57 million tons of CE units. This calculation puts the effective reduction in CE units between 1990 and 2010 at 14 million tons, or 25 percent. Furthermore, CE emission estimates would be about 6 million tons less if the electricity conversion factor for CE units used in this report assumed the U.S. national grid generation based on 60 percent coal, 11 percent natural gas, and 29 percent noncarbon resources rather than generation from 100 percent coal. This would represent about 2 percent of the total annual U.S. carbon equivalent emissions.

1. INTRODUCTION

Steel is such an integral part of American life that its consumption reflects the strength of the domestic economy. Despite competition from materials such as plastics, aluminum, sintered powdered metals, composites, and even wood, steel has remained dominant on both a low cost and high-tonnage basis. Basic industries such as transportation, construction, machine building, mining, and others concerned with energy production and transmission depend upon the unique properties of steel. Steel is also central to the fastener industry: nuts, bolts, screws, nails, staples, and even paperclips are all everyday steel products. Although the beverage can market is now dominated by aluminum, food cans are still made of steel, and while aluminum and plastics have made inroads into the appliance market, that industry remains steel-based as well. Because of these markets and others, consumption of steel is high and will remain so in the future. Current steel consumption averages about 900 lbs/capita (see Figure 1), and with the average population growth rate at about 1 percent per year, this translates into an additional requirement of 1 million tons of steel annually.

However, U.S. steel interests have faced serious threats from foreign competitors. Since the long strike of 1959, imports of steel products and semi-finished steel have increased dramatically (see Figure 2) and have caused prices to remain depressed. Furthermore, trade laws have been unable to regulate the dumping of foreign semi-finished steel (selling below foreign-domestic cost). While beneficial for consumers, these conditions have hurt profit margins, rendering many American companies unable to support the capital investment necessary for growth and stability. Due to foreign competition, the integrated industry was forced to restructure itself between 1975 and 1985 at an enormous social cost for some communities.

The restructuring of the industry has brought major changes to the steelmaking processes. Although more tons of steel have been made in the United States by the basic open hearth process than by any other furnace (Figure 3), none have operated in the United States since 1992 due to restructuring. Obsolete coke ovens and blast furnaces have also been dismantled, leaving a core of efficient facilities. Basic oxygen furnaces are not relined infrequently, not monthly as in the past. The electric furnace has been redesigned to minimize energy consumption and maximize productivity. Barring specific situations, ingot casting has been entirely replaced by continuous casting, and direct hot rolling to near-net-shape products is already in use in some mills. Efficient reheating has been implemented in many of the remaining mills, and downstream finishing processes have been linked to maximize productivity and yield. Through this silent revolution, the industry has remained globally competitive without government subsidies. However, the industry still cannot guarantee consistently adequate profits for many companies in spite of innovations, and stock prices of even the most efficient companies reflect the indifference of the investment community.

While introducing these new processes, the U.S. industry has also intensified its efforts to recycle steel. About 55 percent of all new steel now produced in the United States originate from scrap. Over ten million cars are shredded annually and the upgraded shredder scrap from these cars is returned to the melt shops. Over 65 percent of all scrapped steel cans and appliances are now captured and eventually returned to furnaces (see Figure 4).

The net results of this industry-wide efficiency are remarkable. Although steel yields (shipments per ton of raw steel) remained constant for 60 years, they have risen in the last 20 years from about 73 percent to 95 percent (see Figure 5); average manhours per shipped ton have dropped from 9 hours to 3 hours during this same time frame (under 1 hour for the newest mills); and since 1950 energy consumption has declined from around 45 to 18 million Btu/ton (see Figure 6).

With these reductions in energy consumption in mind, this study aims to accomplish the following:

1. Explain how the historical reduction in energy consumption was achieved and offer guidance for the future.

2. Compare current average energy consumption figures with those for good practices.

3. Project what new technology is available for each process to further reduce energy consumption per ton and estimate potential energy savings.

4. Project how further restructuring of the industry could lower overall average energy consumption per ton.

5. Calculate possible energy savings per ton by the year 2010 relative to 1998.

6. Translate the type of energy used into emissions of carbon dioxide (CO_2) and carbon equivalent (CE) units per shipped ton.

Defining not only the key conversion factors but the adopted boundaries is important in this study. Scrap has been assigned zero energy because if it were not recycled, it would be a waste product sent to landfills. On the other hand, the production of alternative iron (AI) units, such as sponge or pig iron, are energy-intensive; whether they are produced offshore or domestically is of little consequence to the global issue of CO_2 emissions. In this study, only domestic AI products have been assigned energy values. In fact, increased domestic AI production could even slow the industry trend towards lower Btu per ton for EAF mills.

This study has also included the energy required to produce major off-site consumables in the steel manufacturing process (e.g., oxygen, lime, pellets). The energy consumption for these consumables can be easily included or excluded from overall averages. Although the energy associated with their production is large, ferroalloys, electrodes, and refractories have been excluded. Details of conversion factors and unit definitions are outlined in Appendix A, and key conversion factors are shown in the sidebar.

Key Conversion Factors

Fuel	Energy Content
Coal (steam)	12,500 Btu/lb
Coal (coking blend)	13,500 Btu/lb
Coke	13,000 Btu/lb
Natural Gas	1,000 Btu/scf
Electricity	10,500 Btu/kWh*

* (100% coal-based and allowing for coal conversion efficiency)

2. AN HISTORICAL PERSPECTIVE OF ENERGY USE IN THE STEEL INDUSTRY

Although the post-World War II industry was highly productive, most of the processes were highly energy-inefficient. The structural and process revolutions that have made the industry more efficient over the last half-century were unimaginable to the steelmakers of the preceding era. Therefore, 1950 offers an interesting starting point for tracing breakthrough developments in the industry.

At the close of World War II, the U.S. steel industry was globally dominant and very productive. The nation needed steel, energy was inexpensive, and environmental restraints were not yet an issue. The only ominous clouds in the distance were labor's growing wage demands and the depletion of the rich Mesabi ores, which had supplied unbeneficiated iron units to the domestic mills since before the turn of the century.

However, energy requirements were very high just after World War II. The Mesabi ores were not rich by today's South American standards (50 to 55 percent Fe versus 65 to 68 percent Fe), hot blast temperatures were low, and blast furnaces were small. Sintering was rare, and some coke was still being produced in beehive ovens. The result was that coke rates were high (1,850 lbs/ NTHM), which largely contributed to the total energy required per ton of steel (see Figure 7).

Steelmaking was dominated by the basic open hearth (BOH) process, which had been used in the United States since well before the turn of the century and was not replaced until the 1960s. In fact, more 3.6 billion tons of steel were produced in the United States using the BOH process, while today's leading process, the basic oxygen process, has just exceeded 2 billion tons (see Figure 3). Although the open hearth was not as thermally inefficient as might be expected (with its 65 percent hot metal charge and its high use of tonnage oxygen in its later years, the process was almost autogenous), it consumed enormous tonnages of energy-intensive refractories, required many man-hours per ton, and was slow. As energy and labor costs escalated, the process became increasingly uneconomical.

During this period also, all steel was cast into ingots. Ingots were then reheated to about 2,400E F in soaking pits prior to being rolled into slabs or blooms. These slabs and blooms were inspected when cold, conditioned, and reheated to 2,100E F for rolling into semi-finished steel such as hot band and rod.

In the finishing mills, energy consumption was similar to its current level, except for cold rolling (since the average gauge for cold rolled steel is now lighter, the kilowatt hours consumed are higher). Also, there has been a surge in the production of energy-intensive galvanized steel since 1980.

The first major process in the post-war era to impact energy consumption was pelletizing. Pelletizing not only increased the chemical efficiency of blast furnaces by improving gas flow and heat transfer within the stack, but also required (at 65 percent Fe) less burden material and coke to produce hot metal. By 1960, coke rates had dropped to an average of 1,550 lbs/NTHM. Between 1950 and 1965, the burden weight per NTHM dropped 25 percent, and the fuel rate per NTHM dropped 28 percent (see Figure 7). Since that time, the average fuel rate has declined steadily due to the elimination of inefficient furnaces, control of burden distribution through sensors, stack probes and top design, higher hot blast temperatures, external desulfurization, and better coke quality. Coke rates have also declined in recent years due to displacement of coke by coal and/or natural gas injected through the tuyeres.

The basic oxygen furnace (BOF) was introduced in North America in 1954, and as labor and energy costs rose, the transition from the BOH to the BOF became inevitable. By 1969, BOH and BOF annual outputs were equal at 60 million tons each (Figure 8). The BOF is an autogenous process with 70 percent or more hot metal in the charge. However, BOF shops still require energy for activities such as handling off-gas cooling and cleaning, ladle reheating, and running cranes. The development of static and dynamic turn-down control models and sensors has been a primary concern for many technologists since the 1960s. However, the introduction of ladle furnaces in the 1980s alleviated temperature control problems by allowing temperatures to be adjusted after tap.

In the 1990s, slag splashing dramatically extended lining lives and vessel availability for the BOF. The modern BOF, with bottom tuyeres and some post-combustion, can easily produce steel at 500 tons/hour. Its cycle time makes it compatible with slab casting machines. However, the BOF requires 70 to 75 percent blast furnace hot metal, which makes it ultimately dependent upon coke supplies.

The 1970s witnessed the introduction of the minimill, which was based on the combination of an electric arc furnace (EAF), a billet continuous caster, and a rolling mill. Minimills made long products (e.g., bars, rod, sections) exclusively and focused on productivity rather than quality. They were low-cost, low-manpower, and often non-union operations that adopted new technologies, empowered workers, used an inexpensive recycled raw material (scrap), and remained profitable even during hard times. By upgrading furnaces and casters and installing intermediate ladle furnaces, minimills quickly penetrated long product quality markets and displaced integrated mills in that market segment. The timing proved unfortunate as the integrated mills were also coping with the oil crises of 1974 and 1979 as well as pressures and regulations from the newly formed Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA). Interest rates soared to nearly 20 percent at the end of the decade, and capital simply dried up. In 1982, the survival of "big steel" was being seriously questioned.

In the 1980s, continuous casting was widely adopted by the integrated mills (see Figure 8), which acquired capital and technology from Japanese partners in exchange for a share of the automotive markets. These integrated mills restructured themselves to focus on automotive flat-rolled products, specifically new ultra-low carbon and galvanized steel. Continuous casting had two enormous effects on energy per ton: it eliminated the ingot reheating in the slabbing mill, which is a significant reduction in energy for large killed steel ingots with long "hold" times, and it dramatically improved steel yields from liquid steel to shipped product, as Figure 5 previously illustrated. This change reduced the quantity of liquid steel and subsequently the hot metal required to ship a ton of product.

The year 1989 witnessed the launch of yet another revolutionary process: thin slab casting (Figure 9). Slab casting allowed minimills with EAF furnaces to penetrate flat rolled markets and linked hot cast product directly to in-line rolling mills to reduce reheating energy. In addition, thin slab casting has produced automotive quality as well as hot rolled gauges in the cold-rolled gauge spectrum, which is indicative of the potential for these new mills to displace all but the most efficient integrated mills. Also, EAF productivity has escalated in the last decade due in large part to energy conservation technologies.

Because of these innovations, current steelmaking processes seem to have little room for improvement. As the energy intensity of U.S. steel production approaches 15 MBtu/ton, many companies are approaching the practicable "ideal" limits for steelmaking processes. Further energy gains are not likely to arise from new technical breakthroughs, but from further restructuring of the industry. These issues will be discussed in further detail in subsequent sections of this study.

3. AVERAGE ENERGY CONSUMPTION

For all mills, the primary driver to reduce energy consumption is not reduced CO_2 emissions, but cost. For integrated mills in particular, the primary processes are interdependent and integrated into the energy network for the mill. For example, conventional coke plants feed off their own energy and export excess high-Btu gas, which is mixed with lower-Btu blast furnace gas for reheating furnaces. The latter is also used to preheat the stoves and can be used to generate electricity for the plant network through a turbo-generator. This example illustrates that while some processes may operate at less than optimal conditions, these processes produce useful byproducts that, from an overall perspective of mill operations, outweigh the inefficiency. As the industry moves towards more integrated operations in both primary and finishing mills, this balance between productivity and energy consumption becomes increasingly significant.

A number of recent studies have addressed energy consumption for the steel industry. In a study led by R. Fruehan, theoretical minimums for several basic processes were calculated and then modified to reflect several real-world conditions (Fruehan, 2000). The study showed the potential variability for selected processes when real-world conditions are imposed on the ideal process. The authors of an

International Iron and Steel Institute (IISI) study surveyed worldwide practices, examined new technologies for further reducing energy consumption, and made projections concerning energy consumption figures (IISI, 1998).

This current study estimates the energy consumed for sustained good practices (i.e., those that are better than average, but not the best), which are then compared with data for present average energy consumption. Unfortunately, the available data do not allow for the average energy to be calculated for each process, but separating the energy consumed by minimills from that consumed by integrated plants is possible. Data in this report for average energy consumption per shipped ton in 1998 were obtained from American Iron and Steel Institute (AISI) and IISI statistics, updated studies by Energetics, and a recent Steel Manufacturers Association (SMA) survey of minimills. It must be stressed that the reported figures for energy intensity depend strongly upon the boundary conditions selected for the study. For example, pelletizing (70 million tons per year) and limestone calcination (12 million tons per year) add 0.168 quad (Q) to the overall annual energy consumption by the U.S. steel industry (1.682 Q), which is a 10 percent increase.

It should be noted that there are some discrepancies in the lime consumption data. AISI reports a lime consumption by steelmaking furnaces of 4.0 million tons in 1998, while the U.S. Geological Survey reports 6.7 million in their annual lime survey. Neither figure seems reasonable when looking at process consumption figures. However, for this study, 6.1 million tons will be used. Therefore, this report assigns 120 lbs/shipped ton to both BOF and EAF operations, which includes ladle furnaces and hot metal desulfurization. The energy required to produce this lime is 0.038 Q.

In calculating energy consumption, arguments could be made for including the energy associated with other energy-intensive products manufactured for the industry (e.g., electrodes, ferroalloys, refractories, imported direct reduced iron, etc.), but this energy has been excluded from this report. The average energy per shipped ton in 1998 for the industry was obtained by adding the energy used for pelletizing and limestone calcination to the total for ironmaking/steelmaking energy requirements and then dividing this sum by the total shipped tonnage (102.4 million tons), which yields 18.07 MBtu/ton.

SMA obtained energy data from a broad spectrum of minimill plants in 1998 and edited the data to calculate energy per shipped ton. Responses from mills covered over 25 million tons of capacity, and the data show several interesting results (see Figures 11, 12, and 13).

1. *Electricity (Figure 11):* The correlation between plant tons and kilowatt hours over a wide range of production shows that the use of electricity outside the EAF is significant. With an average of 770 kWh/shipped ton and a typical EAF consumption under 500 kWh/cast ton, a significant amount of energy is used for auxiliary equipment in the melt shop, rolling, oxygen production, and general utilities.

2. *Natural Gas (Figure 12):* The scatter is greater because some plants heat treat while others ship directly from the mill. This consumption also covers variable scrap preheating operations, ladle heat, reheat furnaces of various efficiencies, and heat treating operations as well as plant steam generation. A reasonable estimate for consumption is 2.0 MBtu/shipped ton since the melt shop alone could easily account for 0.5 to 1.0 MBtu/ton.

3. *Oxygen (Figure 13):* Primarily, this data covers melt shop usage, and the scatter is evident. The oxygen consumption, at 1,290 scf/shipped ton, is high although there are a number of data points around the 800 scf/ton level. It is difficult to determine whether the excessive usage by some shops is beneficial or whether it is a waste of oxygen.

If 0.65 MBtu/ton are added for carbon usage in the EAF, the Btu per shipped ton for the minimills from this survey comes to about 11.30 (13,100 MJ/tonne) as shown in Table 1. This includes the energy to calcine lime, but may count some kWh for on-site oxygen generation twice.

Table 1. Energy Intensity of EAF Steel Production

Input	Amount (units as given per ton of steel shipped)	Energy Requirement (units as given)	Energy Requirement (MBtu/ton of steel tapped)
Electricity	770 kWh	10,500 Btu/kWh	8.09
Coal	50 lbs	13,000 Btu/lb	0.65
Oxygen	1,000 scf	175.0 Btu/scf	0.18
Natural Gas	2.0 10^6 Btu	--	2.00
Lime	120 lbs	3125 Btu/lb	0.38
Total	**--**	**--**	**11.30**

The increase of EAF steel in the product mix has led to a significant decrease in the overall energy consumption per shipped ton. Since 44 percent of the industry shipments in 1998 were from minimills, the energy consumption of this sector can be subtracted from the total, resulting in a figure of 23.4 MBtu/ton for the integrated sector.

Average data fail to provide perspective on what is a reasonable energy per shipped ton figure for modern plants using technology installed in the last decade. In the following section, this issue is addressed with data acquired from the literature and private communications on sustained good practice operations. A comparison with average data will then be made to show the potential energy savings with existing technology.

4. GOOD PRACTICE ENERGY CONSUMPTION

In this section, a series of processes in both the integrated and minimill sectors are analyzed in detail to estimate "good practice" energy consumption. As stated earlier, a good practice must be sustainable with today's technology. The steelmaking processes include casting and ladle furnace operations.

A. Pelletizing

Pellet production is critical to U.S. blast furnace operations, particularly with the increasing environmental pressure being placed on sinter plants. The average pellet-to-sinter ratio in the United States is about 6 to 1, and pellet consumption has exceeded 70 million tons annually in recent years (AISI, 1998). The energy expended for pelletizing depends on whether the processed raw ore is hematite or magnetite. The oxidation of magnetite (Fe_3O_4) to hematite (Fe_2O_3) is exothermic, reducing the thermal requirements of the process by over 100 percent (Roston, 2000).

Bouman reports a total energy of 1.86 MBtu/ton pellets (2,160 MJ/tonne) for a mixture of oxides (Bouman, 1983). IISI reports 1.09 MBtu/ton (1,262 MJ/tonne) for one on-site hematite plant (IISI, 1998). The Bouman data are preferred because they relate to a time when pellet production was highly active, whereas the IISI data encompasses efficiencies introduced since 1983 that have now been offset by the trend towards fluxed pellets in which limestone must be calcined during induration.

B. Sintering

Sinter plants convert iron-containing waste products (e.g., pellet fines, dust, scale, BOF slag) into a material which, when charged to blast furnaces, is reduced to recoverable iron units. Sinter production has declined in recent years to about 12 million tons (one company produces one-third of this amount).

Bouman reports 2.22 MBtu/ton (2,580 MJ/tonne) of superfluxed sinter. IISI reports 1.56 MBtu/ton (1,818 MJ/tonne) for an average of seven plants. No mention is made of sinter quality, and limestone calcination does increase consumption.

C. Cokemaking

Gases generated during the coking process are used in the operation of the coke plant. Credit is also given for net exports of gas and byproduct chemicals.

Bouman's report accounts for variables such as dry coal, net export gas, chemicals, and furnace coke as well as breeze. Although the data are for 1 ton of furnace coke, Bouman's coke has a Btu content of only 12,200 Btu/lb, whereas AISI/SMA and Energetics, Inc. (IISI data are for non-U.S. plants and are not quoted) use 13,000 Btu/lb (Energetics, 2000). This latter data reduces the net energy consumption at the coke plant to 5.11 MBtu/ton (5,940 MJ/tonne) dry furnace coke, but increases the energy used in hot metal production. The coke has a Btu content of 26 MBtu/ton (30,230 MJ/tonne).

D. Blast Furnace Ironmaking

The blast furnace is the cornerstone of integrated steelmaking. Coke is essential as both a reductant and a fuel and also plays a pivotal physical role in creating a strong, permeable burden and allowing effective slag/metal drainage. While there are limits to how much coke requirements can be reduced, without coke, large, efficient blast furnaces would not exist. (Ponghis, 1998).

Several papers have been presented recently that illustrate the current and potential achievements of modern blast furnaces (Ponghis, 1998; Hille, 1997; Poveromo, 1999). High productivity levels for sinter and pellet burdens and for various fuel injectants at the tuyeres have been reported worldwide for medium (23.6 ft, or 7.2 m) and large (48.5 ft, or 14.8 m) furnaces. These levels also imply optimization of other variables, such as coke quality, high temperature hot blast with some O_2 enrichment, low-slag volumes, and control of coke-burden distribution to maximize reduction efficiency. In this report, however, the key variable is fuel rate.

In the United States, pulverized coal injection is currently favored for blast furnace ironmaking over natural gas or oil despite the initially higher capital investment. Initially in the 1960s, natural gas was preferred because it was easy to handle and many small furnaces could be easily equipped for it. However, natural gas cracks endothermically at the tuyeres, requiring higher hot blast temperatures and/or O_2 enrichment. The injection levels for natural gas in the United States vary from 40 to 200 lbs/NTHM with an average of about 80 lbs/NTHM (40 kg/NTHM) *(I&SM*, 1998). Coal has been injected at much higher levels such as 450 lbs/NTHM or 225 kg/NTHM at U.S. Gary, but the average is closer to 220 lbs/NTHM (Schuett, 1996).

Calculating fuel rates or even comparing equivalent coke rates is difficult due to the replacement ratio used and the Btu content of the displaced coke, both of which vary from plant to plant and country to country. Ponghis cites a replacement ratio for coal of 0.8 (1 lb of coal replaces 0.8 lbs of coke) (Ponghis, 1998). In this study, a ratio of 1 to 1 is assumed to simplify matters. Based on this assumption, the most efficient U.S. blast furnaces are operating at coke rates of about 650 lbs/NTHM (325 kg/NTHM) with coal/gas/oil injection rates of 300 lbs/NTHM (150 kg/NTHM) for fuel rates of 950 lbs/NTHM (475 kg/NTHM). Since these fuels contain only 90 percent carbon, the carbon rate is close to 900 lbs/NTHM. The primary drivers for using injectants are the rising costs associated with the shrinking coke supply and the low cost of coal.

As Bouman points out, the blast furnace operation itself requires energy. If Bouman's figures are modified to reflect the recent average U.S. burdens, coke rates, and a higher Btu/lb coke, the net total energy required to produce hot metal is 15.48 MBtu/NTHM, as shown in Table 2. However, it must be recognized that no two furnaces in the United States run alike, and the carbon rate can be lowered by using sponge iron or scrap in the burden and increasing O_2 tuyere injection rates to higher levels. Therefore, market needs and costs become critical factors in determining energy requirements for blast furnaces.

Table 2. Net Energy Consumed in U.S. Hot Metal Production (Good Practice), 1997–1998

Operation	Energy Requirement (MBtu/Ton Output)	Amount Required (Tons/NTHM)	Energy Requirement (MBtu/NTHM)
Sintering	2.2	0.24	0.53
Pelletizing	1.9	1.3	2.47
Coke Plant	5.1	0.325	1.66
Coke	26	0.325	8.45
Tuyere Injectants	25	0.15	3.75
Blast Furnace	--	--	3.22
Subtotal	**--**	**--**	**20.08**
Top Gas Credit	--	--	(4.60)
Net Total	**--**	**--**	**15.48**

E. Alternative Ironmaking (AI)

The scrap market is often erratic. As mills generate less in-plant scrap and customers maximize their yields, the threat of a shortage in prime prompt scrap increases. Millions of tons of obsolete scrap do exist, but the cost of recovering it increases annually. As a result, some domestic EAF mills are trying to control costs by investing in on-site AI production units to supplement purchased scrap. This is an interesting trend given that for over 30 years the idea of onshore AI production has been limited due to low gas, ore, and labor costs in Mexico and South America. Most foreign plants produce captive DRI (a form of AI), and the supply of merchant product has been limited, which until recently led to long-term contracts with U.S. steel mills. Now, with competition from Brazilian and Russian pig iron as well as more merchant capacity both onshore and offshore, the situation is changing. Table 3 illustrates that the usage of AI by EAF mills in the United States is still modest and well below the normal tonnage level for exported scrap (i.e., normally 10 million tons annually).

Table 3. Iron Unit Consumption in the U.S. Steel Industry (Million Tons), 1998

Material	EAF	Integrated Mills	Exports	Imports
Scrap	42.0	15.5	5.6	3.0
Blast Furnace Hot Metal	0.0	53.0	0.0	0.0
Non-BF Hot Metal	0.0	0.0	0.0	0.0
Cold Pig	4.4	0.0	0.0	5.7
Sponge Iron	1.9	0.4	0.0	1.4

The dominant element of AI production is the shaft furnace, which uses natural gas (as a reductant) as well as a charge of pellets and screened ore. Midrex and HYL produce over 80 percent of the world's sponge iron using this process (Midrex, 1998). In the United States, the shaft furnace is currently used by Georgetown Steel, American Iron Reduction (AIR), and Tuscaloosa. Minnesota Iron and Steel also plans to use this process.

Rotary hearth reduction is also attracting attention because it uses cheap coal and ore fines, as well as recycled byproduct oxides such as scale, dust, and sludge. However, the product of rotary hearth reduction is not a suitable raw material for the EAF because of the ash and sulfur contributed by the coal. New developments add a submerged arc furnace to create a chargeable liquid product.

Although the carbide process appears to be defunct, fluidized beds are too expensive, and kiln technology is too energy intensive, some relevant energy data for all of these direct reduction processes are shown in Table 4. Energy consumption levels are 50 percent higher than the theoretical minimum (12 MBtu/ton versus 8 MBtu/ton). Generally, such material is used in EAF furnaces to control costs and residual chemistry, not reduce energy per ton.

F. Basic Oxygen Steelmaking

Although basic oxygen steelmaking is considered an autogenous process, it is not a zero-energy process. The installation of ladle furnaces and vacuum degassers has increased energy consumption in BOF shops. The lime and oxygen used also require energy for their production, and the energy needed to operate facilities such as baghouses, cranes, ladle preheaters, torches, and tundish driers must be considered. However, this additional energy consumption is minor in comparison with the energy associated with hot metal. With declining silicon contents, the percent of hot metal in the BOF has increased to about 75 percent. Yields through the caster from charge metallics are around 90 percent. Table 5 shows energy requirements for a BOF shop, which includes slab casting and ladle furnace operations.

The operation itself requires 1.2 MBtu/ton of steel (the sum of the energy requirements of all inputs in Table 4 except for hot metal). The energy per ton of steel depends greatly upon the percentage of hot metal. A 100E F increase in temperature or a 0.4 percent increase in Si content can reduce the percentage by 2.5 percent or 0.4 MBtu/ton of steel.

Table 4. Generalized Data on Alternate Ironmaking Processes (all values per metric ton of output)

Process	Electricity (kWh)	Nat. Gas (MBtu)	Coal (metric ton)	Total Energy (MBtu)	Capital ($)	Operating Cost (Venezuela) ($)	Operating Cost (Gulf) ($)
Shaft	110–130	9–10	0	11–12	150–200	102	130
Fluidized Bed	110–150	11–12	0	13–14	200–250	97	
Rotary Hearth	90–120	2–3	0.35	12–13	175–230	--	112
Kiln	70–100	0	0.75	21	240–250	--	--
Carbide	230	13–14	0	16–17	170–300	--	--

Table 5. Net Energy Consumed in U.S. BOF Operations (Good Practice), 1997–1998

Input	Amount (units as given per ton of cast product)	Energy Requirement (units as given)	Energy Requirement (MBtu/ton of cast product)
Hot Metal	0.833 NTHM	15.48 MBtu/NTHM	12.90
Oxygen	1,800 scf	178.5 Btu/scf	0.32
Lime	0.04 ton	6.25 MBtu/ton	0.25
Electricity[a]	25 kWh	10,500 Btu/kWh	0.26
Caster	--	--	0.15
All Other	--	--	0.34
Total	**--**	**--**	**14.07**

[a] Ladle furnace electricity requirements

Recovery of chemical energy in the off-gas is worth about 0.6 MBtu/ton, but using a simple payback time of 12 years, the economics have not yet justified the capital investment in the United States (Worrell, 1999).

G. Electric Arc Furnace (EAF) Steelmaking

While the EAF and BOF steelmaking processes share nearly equal melting output levels in the United States (see Figure 8), the EAF level will probably exceed the BOF level well before 2010. Initially, the EAF process was confined to specialty steel production, but in the 1970s, as capital costs rose and profits in the integrated industry declined, entrepreneurs saw the EAF as a low-cost method of producing steel when coupled with a billet caster and a bar or section mill. These “minimills” focused on long products such as rebar and light sections in which final quality was not as critical as in cold heading or automotive steels. The mills generally produced less than 300,000 tons annually and were built in rural locations throughout the United States.

The integrated mills did not consider minimills to be a threat. However, the younger workforce, seasoned with a few veterans from big steel, embraced the new technology and drove productivity to new levels in non-unionized minimills. The minimills also dealt more easily with environmental issues. Despite the inefficiency of electricity generation and transmission and the crudeness of early operations, the minimills' energy consumption per ton of EAF/cast steel was well under 10 MBtu.

While integrated mills were restructuring in the 1980s, the minimills were producing more value-added products and optimizing operations to maximize productivity and minimize energy consumption. Their activity continued at a rapid pace into the 1990s with breakthroughs into flat-rolled products and site-specific rationalization of raw material utilization. Scrap was no longer the only source of iron units.

For a basic "good practice," the EAF has a 100 percent scrap charge. The ideal minimum energy to heat and melt iron is 1.1 Mbtu/ton (1.3 MJ/tonne). Unfortunately, accomplishing this minimum level takes both time and adequate facilities–adding heat losses from both the furnace and exiting process gases, which increase with tap-to-tap time. Therefore, the goal of furnace designers and operators over the years has been to maximize the rate of energy input to the EAF (power) by superimposing chemical power onto increasing electrical power, while capturing and utilizing as much waste heat as possible (Klein, 1999; Mueller, 1997; Haissig, 1999; Bender, 1997).

Key developments in EAF steelmaking include:

- Use of long arcs to enhance electrical efficiency along with foamy slags for wall protection;
- Use of multifunctional injectors and lances for carbon, oxygen, and oxy-fuel input;
- Combustion and capture of CO exiting the bath (post-combustion);
- Capture of sensible heat in off-gas by cold scrap;
- Ladle furnaces for external adjustment of temperature and chemistry;
- Continuous charging of AI units and furnace designs that permit one-bucket charging;
- Eccentric bottom tapping;
- Computer controls;
- Increasingly powerful transformers.

Many shops are now in the race to shave off every possible minute of heat time. The best shops in the world, including those in the United States, have average heat times of 40 to 45 minutes with 100 percent scrap charges and heat weights of 120 to 150 tons. Power-on times are 30 to 35 minutes with power-off at 5 to 10 minutes (Bender, 1997). The total energy input is what counts (see Table 6). While electricity usage declines, consumption of natural gas, carbon, and oxygen rises. Ladle furnace operations, baghouses, cranes, caster, ladle heating, and other auxiliary services consume an additional 100 kWh or 1.05 MBtu for a total of 6.7 MBtu/cast ton (note that the electrical to chemical energy input ratio is still 4 to 1).

H. Rolling and Finishing

When slab casting was introduced, the concept of hot charging was considered, but was not pursued because the hot slabs would cool before reaching the hot strip facilities that were typically built at a distance from melt shops and cold conditioning was still mandatory to maintain quality. As cast slab quality improved, warm charging became feasible, and a direct charged mill was built in Cleveland by

LTV (discussed later in this report). One difficulty that has arisen is that melt schedules are based on heat lots and chemistry, whereas rolling schedules are based on order sizes and product dimensions.

Table 6. Net Energy Consumed in U.S. EAF Operations (Good Practice), 1998

Input	Amount (units as given per ton of steel tapped)	Energy Requirement (units as given)	Energy Requirement (MBtu/ton of steel tapped)
Electricity*	500 kWh	10,500 Btu/kWh	5.25
Carbon	50 lbs	12,500 Btu/lb	0.63
Oxygen	1,200 scf	178.5 Btu/scf	0.21
Natural Gas	300 scf	1,000 Btu/scf	0.30
Lime	0.05 ton	6.25 MBtu/ton	0.31
Total	**--**	**--**	**5.65**

* Includes 100 kWh for auxiliary services

The flat-rolled minimills with simpler chemistries developed a solution to this dilemma. The thin slabs are sheared and fed directly from the caster to an in-line tunnel furnace that acts as a buffer ahead of the hot mill. While this tunnel is essentially a soaking furnace, heat losses occur due to rolling delays and open doors, causing energy consumption to remain in the range of 0.5 to 0.8 MBtu/ton, compared to 2.0 MBtu/ton for modern cold slab furnaces and 1.1 MBtu/ton for new billet furnaces. The theoretical value for heating cold steel to rolling temperature is 0.7 MBtu/ton (810 MJ/tonne). The theoretical energy for reduction by rolling is small (25 MJ/tonne or 0.022 MBtu/ton), but, in reality, 100 kWh (or 1.05 MBtu/ton with the coal conversion factor) is typical.

While this study does not examine the various types of cold rolled steel produced by the integrated mills, much more energy is spent producing tinplate and galvanized steel than standard cold rolled steel. In presenting the data, the various finishing operations have been divided up for each major product category.

I. Motors

The steel industry uses about 43 billion kWh annually of which at least half is for EAF melting and refining activities. This leaves about 22 billion kWh associated with such items as motors or fans. The DOE has projected that about 12 percent of this energy could be saved if more efficient equipment and systems replaced the existing facilities (Xenergy, 1998). This represents a potential savings of 0.027 Q (22 billion kWh x 0.12 x 10,500 Btu/kWh), or about 0.26 MBtu/ton. Although the technology is available, the steel industry is not fully aware of potential benefits. Also, each plant has hundreds of motors, and the industry's inability to measure savings as well as cost and inconvenience are deterrents to making the change.

5. POTENTIAL ENERGY SAVINGS WITH EXISTING TECHNOLOGY

Good practice operations are sustainable and have been developed around technology which is commercially available. For example, good practices would include thin slab but not thin strip casting. Data were developed for three steelmaking routes, as shown in Tables 7 (for integrated mill operations) and 8 (for two different EAF routes). With this approach, one can anticipate the separate growth of the EAF flat-rolled sector, which impacts not only the future structural changes within the industry but also future energy consumption.

Table 7. Energy Intensity for Good Practice U.S. Integrated Mill, 1998*

Process	Amount Required per Shipped Ton of Steel (U.S. avg. in tons)	Process Energy Intensity (MBtu/ton)	Contribution to Overall Energy Intensity (MBtu/ton shipped steel)
Ironmaking	0.96	15.5	14.88
Steelmaking/Casting	1.09	1.3	1.42
Hot Rolling	0.15	2.2	0.33
Cold Rolling	0.25	4.2	1.05
Plate/Structural	0.15	3.0	0.45
Hot Dip Galvanized	0.24	5.5	1.32
Electrogalvanized	0.06	7.0	0.42
Tinplate	0.07	7.8	0.55
Other	0.08	3.0	0.24
Total Shipped	**1.0**	**—**	**20.66**

* Includes lime, oxygen, and pellet production. Excludes internal power generation and ferroalloys.

Table 8. Energy Intensity for Good Practice U.S. EAF Operations, 1997–1998*

Process	Amount Required per Shipped Ton of Steel (U.S. avg. in tons)	Process Energy Intensity (MBtu/ton)	Contribution to Overall Energy Intensity (MBtu/ton shipped steel)
EAF - Flat Rolled			
EAF/LF/Casting	1.11	6.7	7.44
Hot Rolling	0.7	1.0	0.7
Cold Rolling	0.09	3.5	0.32
Specialty	0.17	5.0	0.85
Galvanized	0.04	4.9	0.2
Total Shipped	**1.0**		**9.51**
EAF - Other			
EAF/LF/Casting	1.12	6.7	7.5
HR Bar	0.53	2.0	1.06
Plate/Str.	0.18	3.0	0.54
Rail	0.02	3.0	0.06
Pipe	0.09	4.5	0.4
Rod	0.15	1.5	0.23
Wire	0.03	5.0	0.15
Total Shipped	**1.0**		**9.94**

* Includes energy to produce lime and oxygen

For each route, the product mix is broken down as a percentage of 1 shipped ton. The steel and hot metal required are then back-calculated using estimated yield numbers, and the energy required per shipped ton for each route is tabulated. It is then possible to compare actual (average) consumption with the potential energy consumption per shipped ton (see Table 9).

Table 9. Potential Energy Savings in the Current U.S. Steel Industry* (MBtu)

Segment	Average	Good Practice	Difference
Integrated Mills	23.4	20.7	2.7
Minimills	11.4	9.8	1.6
Long products (75%)	9.9		
Flat products (25%)	9.5		
Total Industry	**18.1**	**15.9**	**2.2**

*Data are for 1998 when shipments totaled 102.4 million tons

For a 100-million-ton industry, this calculation translates into about 0.2 Q annually. More significantly, the good practice number is less than 1 MBtu/ton above the estimated average consumption for the year 2010 of 15 MBtu. This good practice number implies that the future structural changes in the industry (i.e., the demise of less efficient companies and the continuing trend towards EAF steelmaking) may play a more significant role than new technology.

Table 10 illustrates the breakdown between primary and finishing operations for good practice data. The numbers appear inconsistent because at least 2 million tons of imported semifinished steel are included only in the finishing data. However, the final energy per shipped ton is consistent with the energy intensity data in Tables 7 and 8.

The study next reviewed some new technologies with the potential to impact steel industry energy consumption in the near future. As newer mills introduce these technologies and the more financially stable integrated mills modify their operations to survive, further restructuring of the industry is likely to occur.

6. POTENTIAL ENERGY SAVINGS THROUGH NEW TECHNOLOGY

A number of developments will impact the future energy consumption by the U.S. steel industry:

- Coal-based, onshore, alternate ironmaking production coupled with a pre-EAF melting unit to provide hot metal to the EAF (a negative for energy per ton but a positive for productivity);
- Increased efforts to conserve energy in hot cast products;
- Increased efforts to capture chemical energy in waste gases from processes;
- Increased use of sensors in all operations to improve efficiency;
- Implementation of the motor challenge program.

These developments have been incorporated into the process discussions below. Other developments such as non-recovery coke production, direct smelting, and thin strip casting are also discussed.

Table 10. Summary of Good Practice Energy Use by U.S. Steel Industry, 1998*

	Amount (million tons)	Energy Intensity (MBtu/ton)	Total Energy Use (Q)
Ironmaking			
BOF	53.0	15.5	0.822
EAF-Flat Rolled	n/a	n/a	n/a
EAF-Other	n/a	n/a	n/a
Total			*0.822*
Steelmaking	**Amount (million tons)**	**Energy Intensity (MBtu/ton)**	**Total Energy Use (Q)**
BOF	60.0	1.3	0.078
EAF-Flat Rolled	12.5	6.7	0.084
EAF-Other	36.0	6.7	0.241
Total			*0.403*
Finishing	**Amount (million tons)**	**Energy Intensity (MBtu/ton)**	**Total Energy Use (Q)**
BOF	58.4	4.36	0.255
EAF-Flat Rolled	11.5	2.07	0.024
-EAF-Other	32.5	2.44	0.079
Total			*0.358*
Totals	**Amount (million tons)**	**Energy Intensity (MBtu/ton)**	**Total Energy Use (Q)**
BOF	58.4	20.66	1.207
EAF-Flat Rolled	11.5	9.51	0.109
EAF-Other	32.5	9.94	0.318
Total			***1.634 Q (or 15.9 MBtu/ton)***

* Good practice data for blast furnace include energy for pelletizing;
Other inclusions: Lime—6.1 million tons x 6.25 MBtu/ton = 0.038 Q
Oxygen—3 x 10^8 1,000 scf x 17 kWh/1,000 scf x 10,500 Btu/kWh = 0.054 Q
Excludes on-site energy generation.

A. Cokemaking

Cokemaking in the United States has dropped to around 15 million tons annually. In order to fulfill ironmaking carbon requirements, 6 million tons of imported coke and 5 million tons of pulverized coal injection have supplemented domestic coke production. Although byproduct, non-recovery coke ovens have been operating since 1989 and the Coal Technology Corporation has a proposal on the table for a two-stage, non-recovery system, there is no rush to build new ovens. Capital costs, environmental regulations, and the poor financial returns of most integrated mills have forced most companies to close ovens and import coke. Ispat Inland has a “take and pay” contract with Sun Coal and Coke Company to operate 268 new (1998) non-recovery ovens in East Chicago. There have been operational problems, which are still being resolved. A cogeneration facility provides electrical power to the steel plant, but the lack of coke oven gas with its high CV (500 Btu/scf) means purchasing natural gas for reheating furnaces. The net energy savings is not known at this time.

B. Blast Furnace Ironmaking

Many improvements to blast furnace ironmaking have been made in recent years. Sensors now support automation, maximize yields, and promote cost reduction programs that keep the U.S. steel industry globally competitive. The adoption of probes in the blast furnace helped to optimize gas flow and burden distribution with subsequent benefits in productivity and reduced coke rates. While both sensible and chemical heat are available in top gas, the problem with blast furnaces is the large volume of gas that must be cleaned prior to usage and its low calorific value (CV). Blast furnaces generate about 50,000 scf/NTHM of top gas with low CV (80 to 90 Btu/scf). USX Gary recently increased its usage of top gas from 75 percent to 90 percent by installing a turbo-generator for additional in-plant electricity generation (Moroney, 1999). AISI statistics suggest that 75 percent utilization of BF top gas is normal. The potential energy for recovery by the industry is significant (0.02 Q), but the capital cost for this additional recovery is probably not justified for most U.S. integrated mills, which need capital to meet other priorities (Worrell, 1999).

C. Alternative Ironmaking

New processes are introduced frequently, but the track record for such developments is poor. Furthermore, U.S. companies cannot always adapt foreign successes. One example is HYTEMP in which hot DRI is fed directly to an EAF to enhance productivity (Quintero, 1999). Since virtually no on-site DRI plants exist in the United States (except for Georgetown Steel), the process cannot be applied. Although the technology cannot be directly applied, the overall concept is still valid – charge hot scrap or hot metal with its built-in fuel of carbon.

The direct smelting technologies (e.g., AISI, DIOS, HISMELT, CCF, etc.) have not succeeded in producing iron let alone steel, which was the original objective. The COREX process has proven itself commercially and avoids the need for coke ovens. However, it has a high fuel rate (995 kg/NTHM, double that of the blast furnace), and its economics depend upon utilizing the high-CV top gas either as a fuel or a reductant (e.g., Saldahna). Several U.S. companies (e.g., Weirton, LTV, Geneva) explored the potential for using COREX, but ultimately rejected the technology. HISMELT is possibly coming back to life now that the reactor has been redesigned. If the process can use cheap iron units and a site can be found with available hot blast and material handling facilities, then a semi-commercial process could be developed to make iron within five years. HISMELT is unlikely to be as energy efficient as the blast furnace, but could claim reduced costs per NTHM due to cheap raw materials. There is also interest in the mini-blast furnace for specific sites, but size again operates against lower energy/NTHM than the larger blast furnace (Hille, 1997).

In the last few years, several onshore DRI plants have been commissioned to join the original 1980 operation at Georgetown Steel. They are all based on the Midrex shaft process, which involves natural gas reduction and pellet/sized ore charges. Disadvantages of these plants include the expense of importing oxygen (i.e., iron oxide from South America) and purchasing gas for reducing the charge.

However, EAF-based steel companies operating such facilities do retain more control over raw material costs, quality, and availability.

Coal, rather than natural gas, is the logical choice as a reductant for U.S. plants, but it contains ash and sulfur. Ore fines are a cheap raw material, and both scale and EAF dust need to be recycled. This has led to several parallel developments in which two established processes, a rotary hearth furnace (RHF) and a submerged arc furnace (SAF), have been coupled so that the gangue-rich DRI can be melted to separate carbon-rich hot metal from the gangue. This metal can then be fed to an EAF to enhance productivity. In short, this is the United States answer to HYTEMP (Quintero, 1999).

Iron Dynamics has been the leader in RHF and SAF processes (Bednarz, 1999). Cleveland Cliffs is adopting the REDSMELT process, but can only produce merchant pig unless it builds an adjacent steel mill (Degel, 1999). Midrex is focusing on FASTMELT and is developing a commercial operation at Kobe in Japan (Griscom, 1998). These are all energy-intensive operations that will result in energy charges per Btu higher than those for 100 percent scrap in the EAF. Yet, by increasing productivity and reducing costs, companies that adopt these operations will become more competitive. The net effect will be to displace less efficient minimills and integrated mills without assurance of a net reduction in energy.

Some energy data for these processes were shown in Table 3. Data from Iron Dynamics are shown in Table 11 for rotary hearth furnace and submerged arc furnace operations. This total energy is greater than the energy to produce blast furnace hot metal (15.5 MBtu) and may never be reduced to that value because of the scale of operations and the duplexing operation. The rotary hearth efficiency at Iron Dynamics (ID) appears to be lower than the figures shown in Table 4, which are for metric tons. The ID data depends heavily on the figure for coal consumption, and since experience is limited, this figure could change. At 33 percent hot metal in the EAF charge, the overall melting energy per ton for the EAF will double.

Table 11. Net Energy Consumed in Rotary Hearth Furnace and Submerged Arc Furnace Operations

Fuel	Amount (units as given per ton sponge iron)	Energy Requirement (units as given)	Energy Requirement (MBtu/ton)
Rotary Hearth Furnace			
Natural Gas	3,970 scf	1,000 Btu/scf	3.97
Electricity	100 kWh	10,500 Btu/kWh	1.05
Coal	360 lbs	12,500 Btu/lb	4.50
Total per ton DRI	**--**	**--**	**9.52**
Submerged Arc Furnace			
DRI	1.39 tons	9.52 MBtu/ton	13.23
Electricity	500 kWh	10,500 Btu/kWh	5.25
Lime	150 lbs	6.25 MBtu/ton	0.47
Total per NTHM	**--**	**--**	**18.95**

For steel plants, the increase in productivity for the EAF, the avoidance of EAF dust and scale disposal costs, and control over the quality, availability, and cost of raw material all outweigh the energy issue. If Iron Dynamics succeeds, it will encourage larger EAF shops to replicate its approach.

D. BOF Steelmaking

In the BOF, the use of bombs for dynamic turn-down control has not been very successful. Although the best static charge models can control temperature adequately for today's ladle furnaces, interest in ultra-low C control is still high (ISS, 1998). Measuring vessel contours by laser technology is also important, but only effective if it can be done quickly.

BOF gas is similar to BF gas in that it contains low-Btu heat and must be cleaned prior to being used in the mill. Currently, most U.S. BOF shops dilute and flare the high-CO gas exiting the vessel. Two large steel plants, Taranto in Italy and Boashan in China, have Combined-Cycle Gasification Technology (CCGT) installations (Luessen, 1999; Watanabe, 1999). For the suppressed combustion systems popular in Europe, the CO exit levels are around 70 percent; at 3,000 scf/ton of steel, the recoverable Btu equals about 0.7 M/ton or 0.041 Q for the U.S. industry. Again, the economics in the United States at this time do not justify the investment with its 11.9-year payback (Worrell, 1999). In the United States, Bethlehem installed variable frequency drive fans for one BOF at Burns Harbor to minimize baghouse kWh (AISE, 1999). Although the annual savings were impressive at 15 million kWh, an efficient EAF in a small minimill (500,000 tons/year) consumes 200 million kWh annually. For each plant, economics must be the driver for such retrofits.

E. EAF Developments

There is an enormous amount of activity and potential in the EAF arena as global engineering companies strive to outperform each other. The major goal for EAFs is to maximize power input to the furnace and minimize power-off time, that is, to strive for high productivity at minimum energy per ton levels. Developments can be classified into three categories (although some of the benefits do overlap): chemical, electrical, and shop and furnace design.

1. Chemical

- Hot metal in the charge reduces kWh and increases oxygen and productivity. It requires careful handling when being charged and places a great burden on the baghouse. Electricity requirements are reduced by about 3 kWh/percent hot metal in the charge, which is 100 kWh for a 33 percent hot metal charge (Denier, 1997).

- Multiple burner/lances for carbon, oxygen, and oxy-fuel injection can maintain foamy slag, decarburize efficiently, cut scrap, and burn CO to capture its intrinsic chemical energy (Gitman, 1997). This involves creating CO from dissolved and solid carbon, combustion of CO in and above the slag, and the capture of some of that heat by the steel bath. Oxy-fuel burners have evolved from simple heating units into multifunctional units, which can inject gas and oxygen as well as solid carbon at different ratios.

- The increase in gas, oxygen, and carbon units per ton over the last decade has created a chemical energy input per ton that is significant and demands design changes in furnaces. Typical energy savings are about 1 kWh/ton for every 10 scf/ton oxygen. Therefore, 1,000 scf/ton could reduce electricity requirements by 100 kWh/ton.

- Although foamy slag is a chemical technology, it enhances the input efficiency of electrical energy and protects the side walls from arc radiation. Oxygen can be injected into the slag to burn CO. There is a thermodynamic limit to this combustion, and some CO oxidation is unavoidable (and unmeasurable). As a result, net energy gain is difficult to quantify, but estimates range from 20 to 50 kWh/ton (Anderson, 1997; Woker, 1999).

2. Electrical

Some of the most productive furnaces in the world are DC. One electrode rather than three simplifies a number of activities and reduces electrode consumption by 100 percent. However, the furnace bottom must be carefully maintained, and AC furnaces can now claim an equivalent electrical efficiency. Other factors must be considered when deciding between AC and DC for a new facility.

The application of computer models and neural networks to EAF furnaces has met with some success, and uniform scrap (e.g., from shredders) and the use of AI units will enhance the benefits of modeling (Martinez, 1997). The use of sensors is also critical–sound units can control foamy slag formation, UV units can measure off-gas chemistry instantaneously, and thermocouples can measure bath temperature continuously.

3. Shop and Furnace Design

On the furnace itself, elements such as tap-hole design, fast electrode changing, and continuous charging are reducing power-off minutes, and the focus is now tap-to-tap minutes. The objective is a one-charge heat coupled with continuous AI charging, which has been achieved by designing larger furnace volumes and maximizing scrap density (Mueller, 1997).

The waste gas from the EAF is used to preheat scrap, and efforts to capture as much chemical heat as possible inside the furnace have intensified. The gas is extremely dirty and must be cooled before filtering. Because EPA emission limits for CO in gas leaving the baghouse are stringent, gas leaving the baghouse has no useful chemical energy or sensible heat.

Capturing heat from the off-gases can be accomplished by mounting shafts on the furnace roof, constructing twin shells, or pulling the gases through a side door into a scrap-filled tunnel (Haissig, 1999; Mueller, 1997; Herin, 1995). There are strong advocates for each of the three approaches as well as site-specific reasons to select one design over another. The twin shell concept maximizes power-on time, minimizes power-off time, and permits off-line maintenance. Diverting the hot waste gas from the adjacent shell is not practiced in the United States for safety and productivity reasons. The downside of twin shells is the additional capital required. For all these processes the energy cost per ton will fall, but this advantage is not a primary driver. Productivity is the overarching goal, providing take-away and market demand is present.

Off-gas chemistry from the EAF can be measured instantaneously using ultra-violet scanners. These elements all relate to artificial intelligence systems for EAF control. Additionally, a probe to measure tuyere length in EAFs has recently been developed (Braconnier, 1998).

In the future, more emphasis will be placed on streamlining the tapping operation, using scrap to capture waste heat, excluding air from the furnace, and developing different electrode configurations and hybrid EAF-BOF operations (IISI, 2000; Bender, 1999; KES, 1998; Mannesman, 1999). With long strings of caster heats, continuous steelmaking is already occurring; the furnaces and ladle furnaces can still operate as efficient batch units and buffers without a significant energy penalty. Just as the minimills are moving towards hot metal in charges, integrated companies may be forced to into EAF ventures to survive.

IISI recently published a global projection of future EAF operations. (Klein, 1999). Electrical power has been supplemented by chemical power such that electricity requirements are approaching 200 kWh/ton while 30-minute tap-to-tap times are now conceivable for heat sizes over 100 tons. Even with 2,000 scf/ton of oxygen and 60 pounds of charged carbon, the energy intensity remains below 4 MBtu/ton for the EAF operation per se. The energy associated with charged AI units could double this figure, however.

F. Casting

The ultimate goal in casting is to maximize productivity at maximum yield while minimizing defects and manpower. Each mill has its own priorities, and while the net effect on energy savings is quite unpredictable, the drive to reduce costs and increase market share through service and quality remains strong.

Casters are fitted with mold sensors to avoid breakouts and measure heat transfer (Brimacombe, 1993). It is only a matter of time before cast slab or billet quality is perfected by controlling the heat transfer variables. For rolling, in-line devices now measure hot surface rod quality, while for flat rolling, surface inspection devices measure the surface quality of cold rolled sheet and distinguish between real defects and artifacts (Roberts, 1999; McManus, 1999).

Strip casting is another new technology. Strip casting projects in Canada have been abandoned, but Nucor has signed a license with BHP to pursue the technology in the United States. Although Japan, Europe, and Australia have invested countless dollars and years in this technology, they have yet to produce AK steel, which is the basis for prime automotive and coated products. Assuming AK steel is produced (an enormous assumption since Al_2O_3 formation, or clogging, is still a major issue in slab casting, and the cast sheet product cannot be conditioned to remove surface defects), casting speeds must be increased to well above 100 m/minute to build even a modest plant of 500,000 tons/year. Otherwise, the manpower per ton rises sharply, and the production of carbon steel would not be economically attractive.

Strip casting seems destined for specialty steel niche markets and will probably have little impact on energy conservation through 2010 (Cramb, 1988). From an energy saving perspective, the major impact would be an elimination of the tunnel furnace and a minor reduction in rolling energy. With 2 million tons of production by 2010 and a 0.6 MBtu/ton savings, the overall energy conservation would be 0.0012 Q or 0.01 MBtu/ton for the industry.

G. Rolling and Finishing

If the 95 million tons of cast products made in the United States each year cool from 2,100E F to room temperature, the lost energy is 0.064 Q. Reheating these products to rolling temperature requires about 0.15 Q; however, most integrated mills use coke oven gas to supplement natural, and credit for this coke oven gas has already been claimed. The total natural gas consumption for reheating is likely closer to 0.11 Q.

A number of factors prohibit mills from feeding hot cast product directly to a rolling mill. The primary factor for integrated mills is plant layout, which evolved long before casting was a reality. LTV Cleveland built a direct charge complex in the 1990s, made possible by the DHCC schedulers' access to the complete order book for the Cleveland District, which allowed them to select orders for their mill. A stand-alone facility would not be practicable. Yet the DHCC reheat furnace still consumed energy–0.5 to 1.0 MBtu/ton (Nelson, 2000).

For minimills, the problems with rolling and finishing are product mix and order size. As mills continue to move towards value-added products, quality criteria become more stringent, and the need to inspect and condition cast surfaces becomes critical. One approach to solve these problems is to install in-line or end-of-line inspection units. The drawback to this approach is that if signals are misinterpreted, high yield losses can result. The ultimate solution is the use of sensors on the casters to ensure surface and internal quality as the product exits the caster.

Sensors solve the inspection problem, but not those associated with order size. Rolling mill schedules for rod mills, for example, are based on diameter rather than chemistry, with many portions of different heats comprising a size schedule. Downtime for size changes can be as great as 35 percent of the mill operating hours, and during this time furnaces are still heating, albeit at a reduced rate. The bottom line is that efficient reheat furnaces with elements such as recuperators, low-NOx burners, and computer controls for managing firing rates in relation to delays will reduce reheating energy for cold steel to about 1.1 MBtu/ton.

The future energy savings in reheating operations for the industry among hot steel, warm steel, and cold steel cannot be certain, but 25 percent, 25 percent, and 50 percent in savings, respectively, through 2010 seem reasonable (see Table 12).

7. POTENTIAL ENERGY SAVINGS DUE TO STRUCTURAL CHANGES IN THE U.S. STEEL INDUSTRY

New technology spurs structural change. When established companies fail, oftentimes it is because they have failed to modernize. They are then replaced by new companies that have adopted the latest technology and different processes. While productivity and markets are still the key drivers today, energy is moving up on the priority list as "greenfield" companies locate to sites where utility contracts and availability minimize costs.

Since the beginning of WWII, when EAF production in the United States was less than 1 million tons, the open hearth along with ingot casting and blooming mills have all been replaced. The basic oxygen process, continuous casting, and the modern EAFs replaced these facilities, while the blast furnace has been modernized beyond recognition. The result has been a huge increase in yield from raw steel to shipped product, as well as the adoption of less energy intensive processes such as the EAF. Energy consumption per ton has plummeted from over 40 M to under 20 MBtu/shipped ton in two generations. Because of such effects, identifying factors that drive the industry towards specific processes and away from others is important in assessing overall energy consumption in the future.

The U.S. per capita consumption of steel goal should remain at 900 +/-200 lbs. With an annual population growth rate of about 1 percent, the United States will consume around 130 million tons in 2010 (assumes a population of 293 million). Steel consumption would decrease from the 140 million of 1998–1999.

Table 12. Potential Natural Gas Savings in Reheating, 2010[a]

Steel	Share of Production (%)	Amount (million tons)	Reheating Energy Requirement (MBtu/ton)	Total Reheating Energy Requirement (trillion Btu)
2010 Estimate				
Hot	25	25	0.40	10.0
Warm	25	25	0.80	20.0
Cold	50	50	1.10	55.0
Subtotal	**--**	**--**	**--**	**85.0**
Credit for Coke Oven Gas				10.0
Net Total	**--**	**--**	**--**	**75.0**
Current Consumption				
Coke Oven Gas	--	--	0.17	17.0
Natural Gas[b]			1.50	150.0
Total	**--**		**1.67**	**167.0**
Total Potential Savings (2010)	**--**	**--**	**0.92**	**92.0 (0.92 Q)**
Total Potential Natural Gas Savings (2010)	**--**	**--**	**0.75**	**75.0 (0.75 Q)**

[a] Based on total production of 100 million tons of steel
[b] Assumes 75% natural gas for reheating

This study's projections, which extend through 2010, are based on the following predictions and are shown in Table 13:

- Net Imports: These will decline to about 25 million tons if the world economy remains stable and demand for steel outside the United States increases.

- Integrated Mills: These will decline to 50 million tons of shipments. The investments by the major mills have been too large to abandon such facilities, and efficient blast furnace capacity is good for at least 40 to 45 million tons of hot metal. However, the importing of inexpensive slabs is a possibility and could result in the closing of some primary facilities. This threat raises the question of actual energy consumption by integrated mills (i.e., the boundary condition issue). For example, Brazil claims to produce charcoal pig iron while sequestering CO_2 and producing inexpensive slabs in the process. (Sampaio, 1999). Another possibility is that integrated mills will adopt hot-metal-based EAFs. If blast furnaces are taken off-line and are replaced by EAFs, energy purchased externally will be required. Importing semi-finished steel is not an effective way to maintain a strong U.S. steel industry.

Table 13. Projected U.S. Steel Industry Statistics

	Production (million tons)	Energy Intensity (MBtu/ton)	Energy Use (trillion Btu)
Imports			
2000	35	n/a	n/a
2005	30	n/a	n/a
2010	25	n/a	n/a
Integrated			
2000	60	21.8	1,308
2005	55	20.5	1,128
2010	50	20.0	1,000
EAF - Long			
2000	33	11.9	393
2005	32	11.0	352
2010	30	10.5	315
EAF - Flat I			
2000	10	10.0	100
2005	12	9.0	108
2010	15	8.5	128
EAF - Flat II [a]			
2000	2	15.0	30
2005	5	14.0	70
2010	10	13.0	130
TOTAL			
2000	140 (-35)	17.4	1,831
2005	134 (-30)	15.9	1,658
2010	130 (-25)	15.0	1,573

[a] EAF furnaces with an average of 35% alternative iron charge

- EAF Conventional Mills: These mills will experience a slight decline as some of the smaller mills close due to age and production of a non-competitive product line. Consolidating many small mills under one corporate umbrella (e.g., Nucor, North Star, Ameristeel, CMC, Birmingham Steel, GS Industries) is one strategy that has strengthened the capital base. However, smaller independent companies may not survive.

- EAF Flat Rolled: Current output will double with 40 percent opting for on-site AI production of either hot metal or hot sponge iron to increase productivity for a given shop. Integrated mills may also build EAF shops and charge hot metal, but the capacity to do so is included in the 40 to 45 million tons of hot metal that can be produced. Also, the melting of RHF high-gangue sponge iron may not be confined to electric-based premelters. It could become feed material for a direct smelting process based on oxygen and carbon (e.g., HISMELT or the Japanese NSR process) that integrated companies with auxiliary material handling facilities already in place would adopt (Gull, 1999; Furakawa, 1999). Rouge Steel already has an RHF to handle waste oxide fines.

8. ACHIEVABLE ENERGY SAVINGS BY THE U.S. STEEL INDUSTRY

The average energy per U.S. shipped ton will decline by 2010 from the present 18.1 MBtu/ton (21,000 MJ/tonne) to 15.0 MBtu (17,400 MJ/tonne), while total energy will drop from 1.83 Q to 1.57 Q. This reduction reflects both structural and process changes and includes the energy required to produce off-site pellets (70 million tons), oxygen, and lime as well as the energy associated with imported coke (6 million tons). Because the figure drops significantly (about 2 MBtu/ton or 0.21 Q) when the pellets, oxygen, and lime are excluded, defining the energy inclusions and exclusions is imperative.

Tables 14 and 15 summarize how the projected energy reduction per net ton of shipments from 1998 to 2000 and 2000 to 2010, respectively, might be broken down between the various types of facilities and the new technologies that have been discussed.

The conclusion to be emphasized is that the replacement of inefficient blast furnaces coupled with the potential fuel rate reduction in the remaining furnaces (due to tuyere injectants and burden materials) dominate the energy-reduction picture. The potential to improve the efficiency of reheating through technology and sophisticated scheduling is also key.

Increasing tonnages of sponge iron and on-site hot metal produced from DRI will increase energy per ton for some EAF facilities, but the overall trend over the next decade still reflects a decrease.

The Motor Challenge Program, if fully implemented over the next decade, would lower the overall energy consumption by as much as 0.3 MBtu/ton. However, achieving even 50 percent of this figure would still be commendable. To put 0.3 MBtu/ton into perspective, this savings corresponds to a reduction of 10 lbs/ton in fuel rate at the BF for shipments from integrated mills.

Although the time span for these projections is only 10 years, factors that could skew predictions have already arisen. The electric utility issues are menacing; the lack of profitability and high levels of imports continue to threaten the economic viability of most companies that cannot earn even the cost of capital; and new EPA rules and a possible Kyoto fallout will add costs that cause margins to shrink even further. Despite these threats, the best facilities in our industry match any in the world for quality, productivity, and new technology. The industry will survive, but the implementation of new technology is likely to be slower than desired for the reasons cited above.

The remarkable decrease in energy intensity since 1950 by the U.S. steel industry is shown in Table 16, along with the projected figures for 2000 and 2010. The large drops in the 1980s due to slab casting and in the 1990s due to thin slab/EAF growth have taken the industry to a level at which future savings become more difficult and require more investment per Btu saved.

Table 14. Projected Energy Reduction for U.S. Industry, 1998 - 2000

Process	Energy Savings from Structural Changes (MBtu/ton)	Energy Savings from Technology Changes (MBtu/ton)	Total Energy Savings (MBtu/ton)
Integrated			
Blast furnace fuel	0.7	0.3	1.0
Reheating	--	0.2	0.2
Motor program	--	0.01	0.01
Cogeneration	--	0.01	0.01
Miscellaneous	0.1	0.3	0.4
TOTAL	0.8	0.82	1.62
Average Energy Intensity for Production of 60 Million Tons = 21.8 MBtu/ton			
EAF Long Products			
Melting	0.1	(0.3)	(0.2)
Reheating	--	0.05	0.05
Motor program	--	0.0	0.0
Miscellaneous	--	0.05	0.05
TOTAL	0.1	(0.2)	(0.1)
Average Energy Intensity for Production of 33 Million Tons = 11.9 MBtu/ton			
EAF Flat Products			
Melting	--	(0.9)	(0.9)
Reheating	--	0.2	0.2
Strip casting	--	0.0	0.0
Motor program	--	0.0	0.0
Miscellaneous	--	0.1	0.1
TOTAL	--	(0.6)	(0.6)
Average Energy Intensity for Production of 12 Million Tons = 10.8 MBtu/ton			
Total Industry Weighted Average for Production of 105 Million Tons = 17.4 MBtu/ton			

9. CARBON EQUIVALENT AND CARBON DIOXIDE EMISSIONS BY THE U.S. STEEL INDUSTRY

Fossil fuels account for about 75 percent of primary energy sources in the U.S., and this figure is likely to rise with the decommissioning of nuclear power plants. Total energy consumption per capita is also expected to rise according to the Energy Information Administration (EIA) of the DOE. Since the burning of fossil fuels results inevitably in CO_2 generation, the United States will generate increasing levels of CO_2 per capita. Although the cause and effect relationship between projected global warming and CO_2 levels in the atmosphere has yet to be unequivocally resolved, developing a plan to minimize CO_2 emissions is prudent.

Table 15. Projected Energy Reduction for U.S. Industry, 2000 - 2010

Process	Energy Savings from Structural Changes (MBtu/ton)	Energy Savings from Technology Changes (MBtu/ton)	Total Energy Savings (MBtu/ton)
Integrated			
Blast furnace fuel	0.6	0.3	0.9
Reheating	--	0.2	0.2
Motor program	--	0.1	0.1
Cogeneration	--	0.1	0.1
Miscellaneous	0.1	0.4	0.5
TOTAL	0.7	1.1	1.8
Average Energy Intensity for Production of 50 Million Tons = 20.0 MBtu/ton			
EAF Long Products			
Melting	0.6	0.4	1.0
Reheating	--	0.1	0.1
Motor program	--	0.05	0.05
Miscellaneous	--	0.2	0.2
TOTAL	0.6	0.75	1.35
Average Energy Intensity for Production of 30 Million Tons = 10.5 MBtu/ton			
EAF Flat Products			
Melting	--	0.15	0.15
Reheating	--	0.07	0.07
Strip casting	--	0.15	0.15
Motor program	--	0.02	0.02
Miscellaneous	--	0.06	0.06
TOTAL	--	0.45	0.45
Average Energy Intensity for Production of 25 Million Tons = 10.3 MBtu/ton			
Total Industry Weighted Average for Production of 105 Million Tons = 15.0 MBtu/ton			

Per unit of energy, the emission of CO_2 is 75 percent higher from coal combustion than from natural gas (DOE, 1996). Unfortunately, the steel industry must use coal for coke production since no total substitute exists. The use of coal as a tuyere injection into blast furnaces is also favored over gas. While coal usage has reduced coke rates per NTHM, it has not reduced CO_2 levels. Coal is a cheap fuel and will also be preferred in the onshore AI processes, particularly in the Midwest. Furthermore, coal is the primary fuel (about 60 percent) for electricity generation in the United States (DOE 1998). Natural gas is the exclusive fuel in the finishing mills, except for the use of mixed gas in integrated plants for reheating. Natural gas is not likely to be displaced.

Table 16. Trends in U.S. Steel Industry Energy Intensity

Trend Year	Energy Intensity (MBtu/ton)	Difference Between Trend Year Intensity and 1990 Intensity (%)
1950	45	56%
1960	41	51
1970	37	46
1980	30	33
1990	20	--
Projected 2000	17	13
Projected 2010	15	25

Table 17 splits the industry into two segments and translates the various energy sources used by each into Quads per segment and carbon equivalents (CE). The data for this table were obtained from Energetics, Inc. and from AISI and SMA statistics for 1998. They were then normalized for the projected future shipments in 2000 of 105 M tons (60 integrated, 45 minimill). Considering the estimates involved and the uncertainty in conversion factors for the various energy sources, the total energy use of 1.872 Q is in good agreement with the figure in Table 13 (17.4 M Btu/ton x 105 M tons = 1.827 Q). Multiplying the figures for carbon equivalents by 3.67 (the ratio of CO_2 to C) gives the CO_2 tonnages, which are presented in millions of tons. The emission factors used to estimate carbon emissions from the combustion of various fuels are shown in the sidebar.

Carbon Emission Factors for Fuels Used in Combustion (million tons of C equivalent/quad)

Natural gas	16.0
Coal	28.0
Electricity[a]	28.5
Oil	22.0

Coal-based energy data is a cause for concern. Table 17 clearly illustrates that coal-based energy accounts for about 75 percent of carbon emissions, whether the starting point is coal for coking or coal for producing electricity. However, only 60 percent of U.S. electricity is generated from coal, and natural gas-fired power stations are becoming more prevalent. This discrepancy means that the conversion factor listed above for kWh is too large. The conversion factor could be as low as 18 million tons CE/Q, and that would reduce the total CE figure for the industry by 6 million tons.

Limestone dissociation is another often overlooked contributor to CO_2 emissions. About 11 million tons of limestone are converted to lime off-site and another 1 million tons used on-site at steel plants, resulting in 5.0 million tons of CO_2, or nearly 1.35 million tons of CE annually.

Currently, the steel industry emits about 48 million tons of CE (178 million tons of CO_2) annually, which includes energy for pellet production, oxygen, lime production, and limestone dissociation, and assumes 100 percent coal-based electric power. This figure could be reduced by 12 million tons of carbon if energy for pellets, oxygen, and lime are excluded and a different conversion figure for electricity is used.

Attempts have been made to apply these data for CE units to 2010 and 1990 data for integrated mills and minimills (separately). Both total emissions of carbon (CE tons) and carbon intensity (CE tons/ton of shipped product) are shown in Figures 14 and 15, respectively. The changes projected are smaller than the spread due to the boundary conditions selected. In order to make them comparable with the projected data, the data for 1990 have been prorated for 105 million tons of shipments rather than the actual 85 million tons shipped in that year. The reduction in CE is then 57 to 43 million tons or 14 million (25 percent). If the absolute number for the economic depression of 1990 is taken, carbon emissions through 2010 will remain the same, although projected shipments will have increased by 20 percent.

Table 17. U.S. Steel Industry Energy Consumption Breakdown for 45 M Tons Minimill and 60 M Tons of Integrated Shipments, Based on Rounded 1998 AISI & SMA Data*

	Minimills		Integrated Mills				
	Energy Use (Q)	**Carbon Emissions (million tons)**	**Energy Use (Q)**	**Carbon Emissions (million tons)**	**Total Energy Use (Q)**	**Total Carbon Emissions (million tons)**	**Total CO_2 Emissions (million tons)**
Natural Gas	0.09	1.44	0.31	4.96	0.40	6.4	23.5
Coal	0.02	0.67	0.58	16.10	0.60	16.8	61.5
Electricity (100% from coal)	0.37	10.55	0.08	2.28	0.45	12.83	47.1
Oil	0.01	0.18	0.02	0.44	0.03	0.62	2.3
Electricity for Oxygen	0.01	0.31	0.04	1.23	0.05	1.54	5.7
Coal for $CaCO_3$	0.02	0.50	0.04	1.00	0.05	1.5	5.5
Electricity (Pellets)	0.00	0.00	0.08	2.28	0.08	2.28	8.4
Natural Gas (Pellets)	0.00	0.00	0.05	0.80	0.05	0.8	2.9
Imports of Coke	0.00	0.00	0.16	4.37	0.16	4.37	16.0
TOTALS	**0.52**	**13.65**	**1.35**	**33.46**	**1.87**	**47.1**	**172.9**
Per Shipped Ton	**11.60 MBtu**	**0.30 ton**	**22.50 MBtu**	**0.56 ton**	**17.80 MBtu**	**0.45 ton**	**1.70 tons**
Minus Oxygen, Lime, Pellets	0.49	12.84	1.14	28.15	1.63	41	150
Per Shipped Ton	**10.90 MBtu**	**0.29 ton**	**19.00 MBtu**	**0.47 ton**	**15.60 MBtu**	**0.39 ton**	**1.4 tons**

* Limestone dissociation to make lime = 5.0 M tons CO_2/year

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FIGURES

Figure 1. U.S. Steel Consumption Lbs/Capita

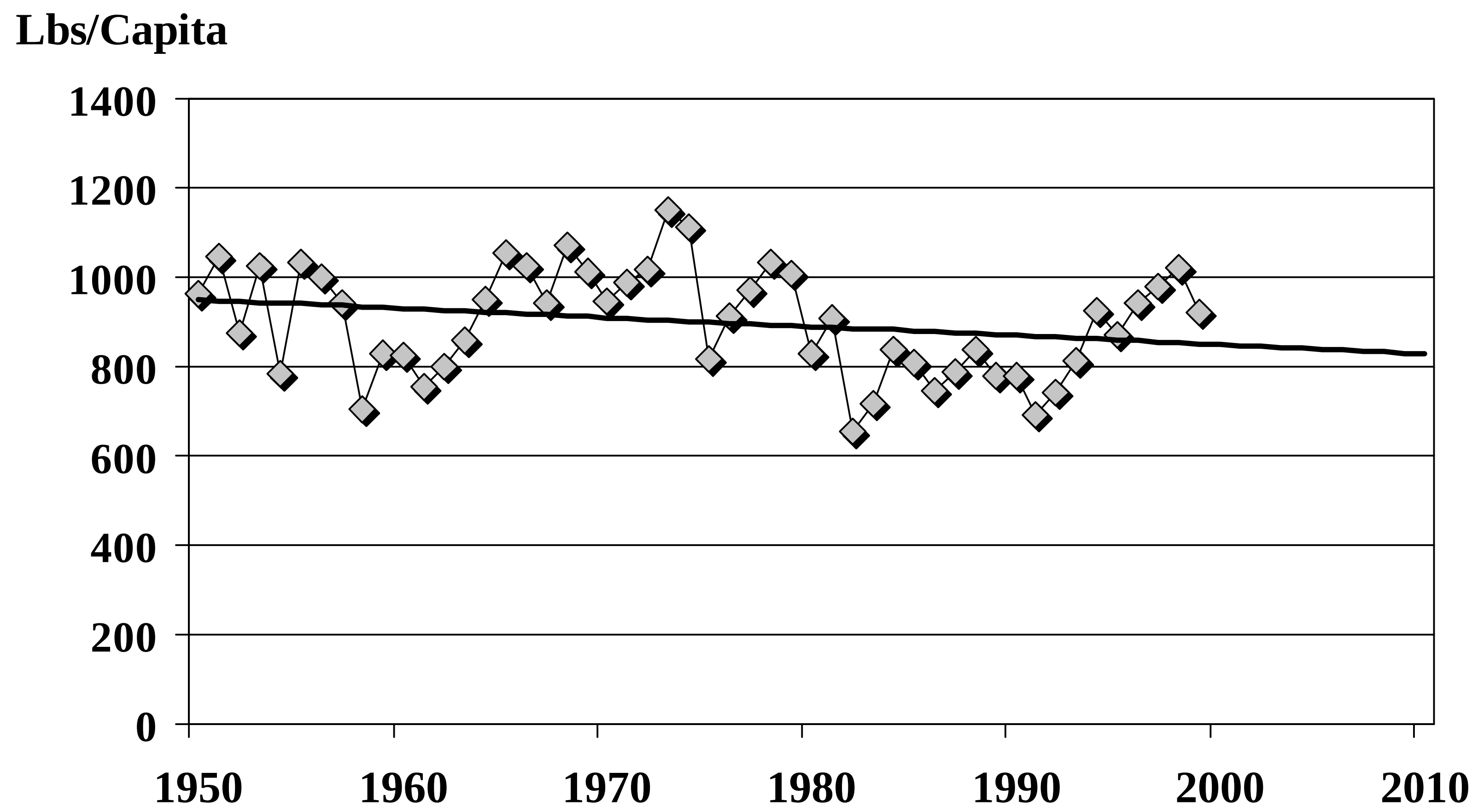

Figure 2. U.S. Steel Imports (Million Tons)

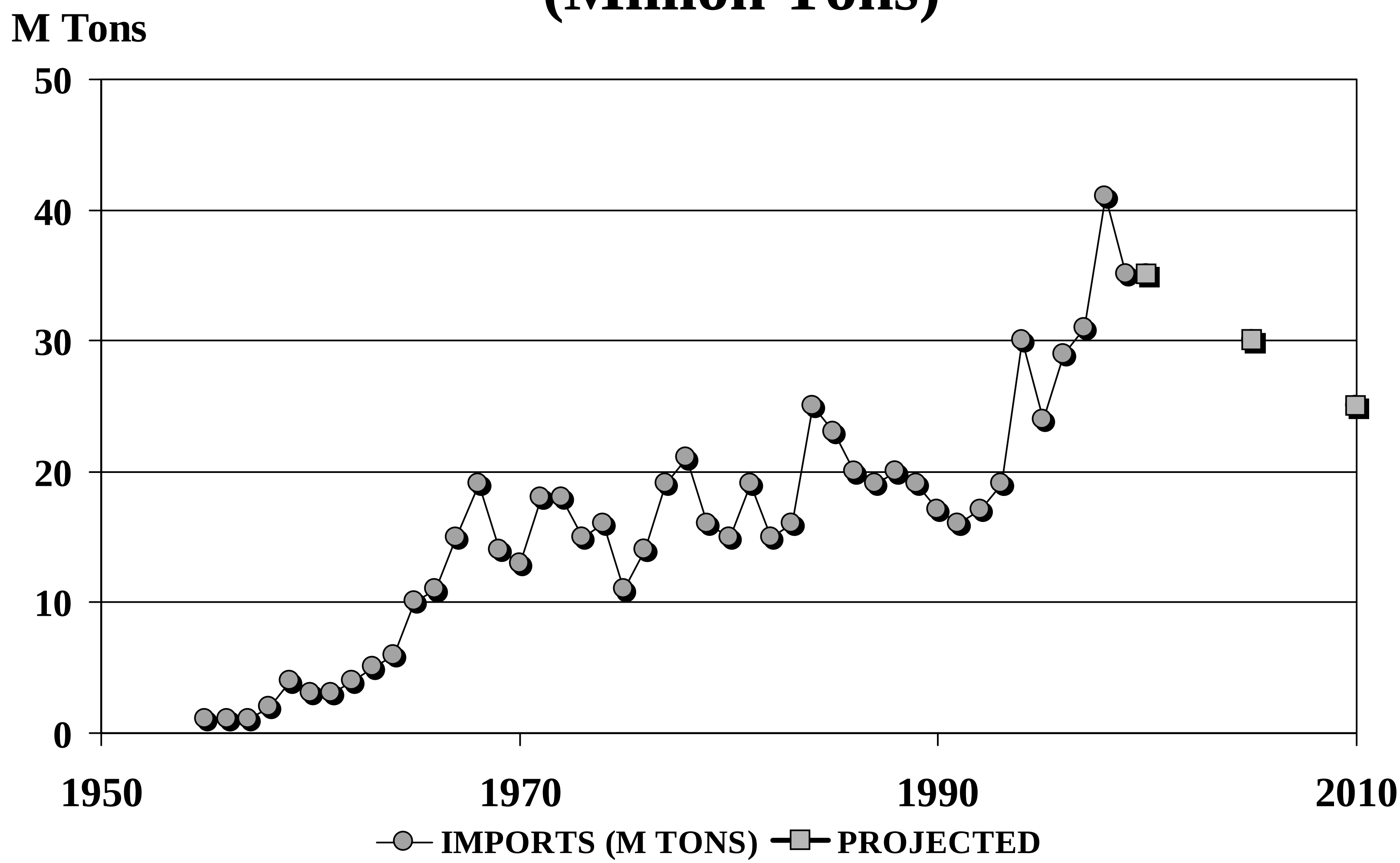

Figure 3. U.S. Steel Production – 1864 to 1999
(Cumulative Total = 7.4 Billion Tons)

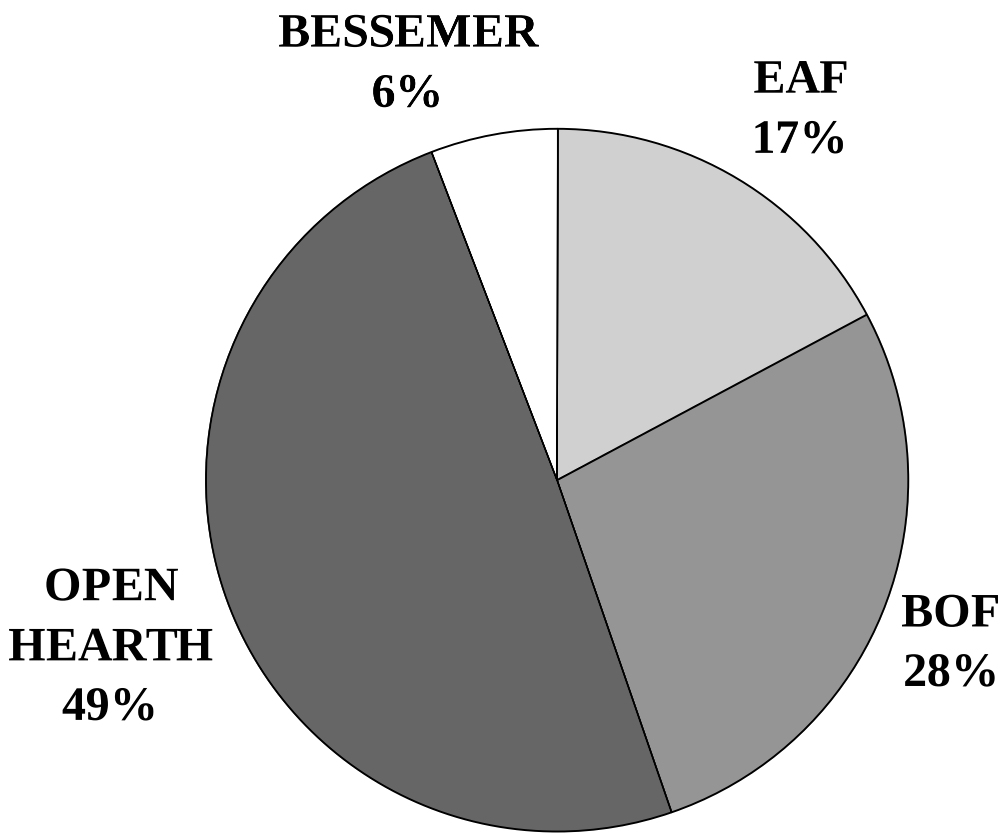

Figure 4. Recycling Steel Durable Goods

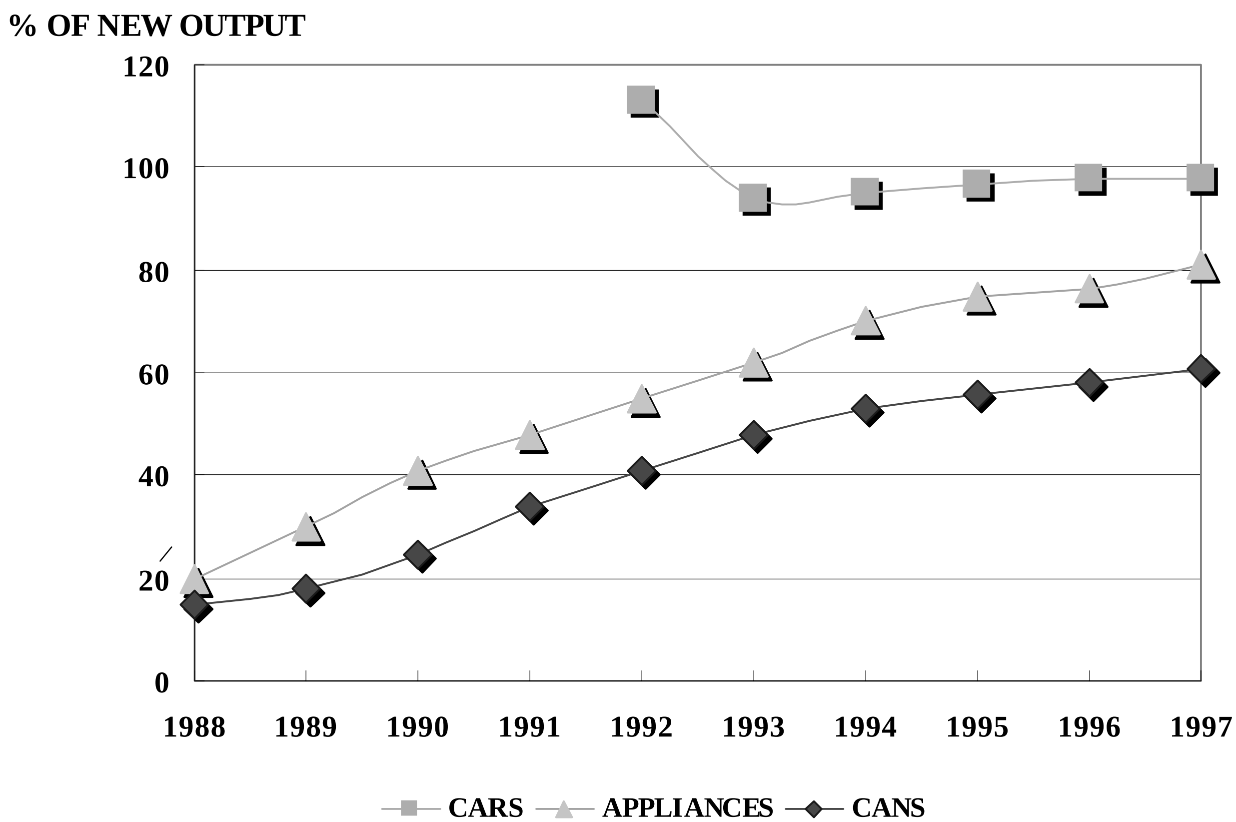

Figure 5. U.S. Continuous Casting and Yields

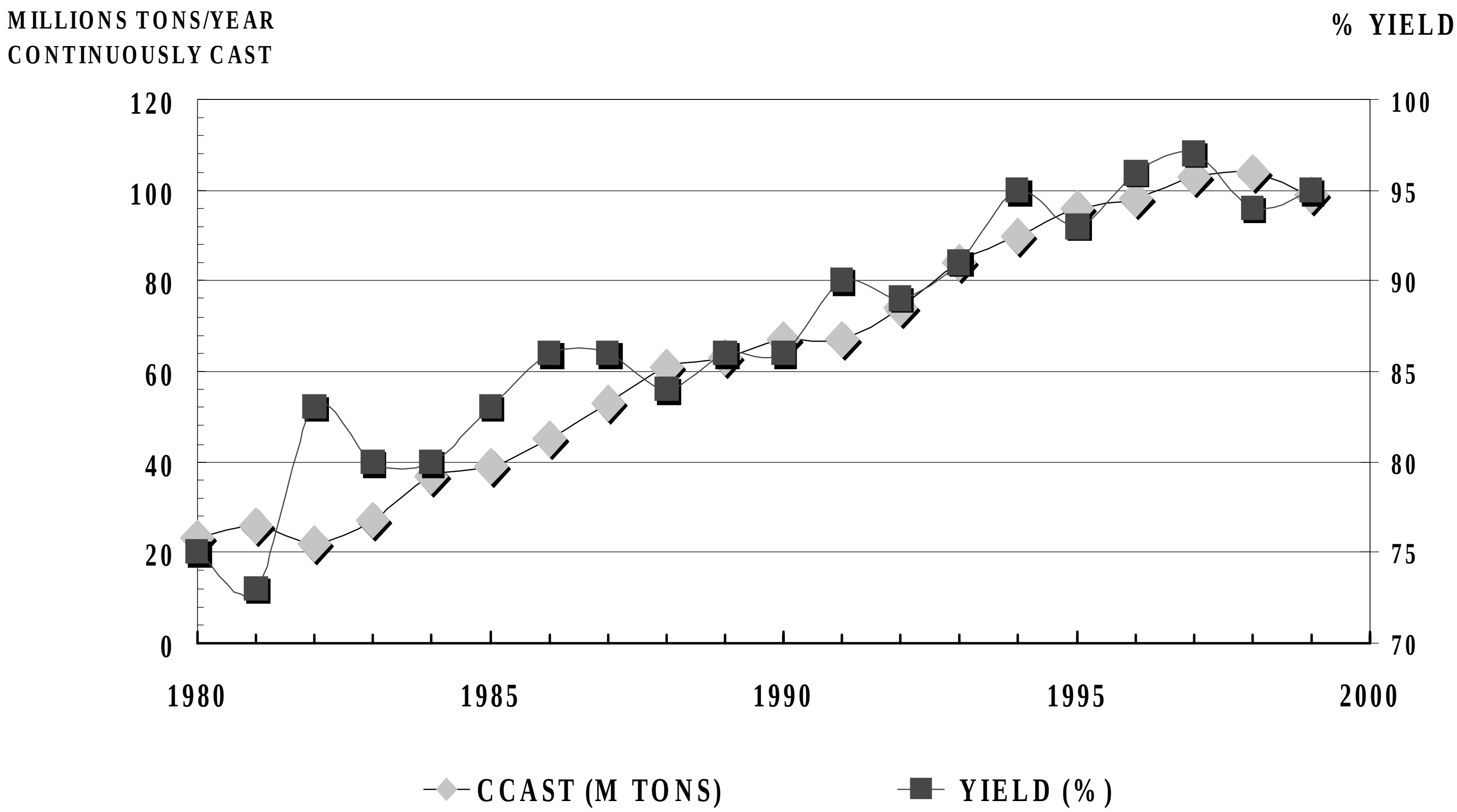

Figure 6. U.S. Steel Industry—Energy/Ton
(Includes Btu For O_2, Pellets, CaO)

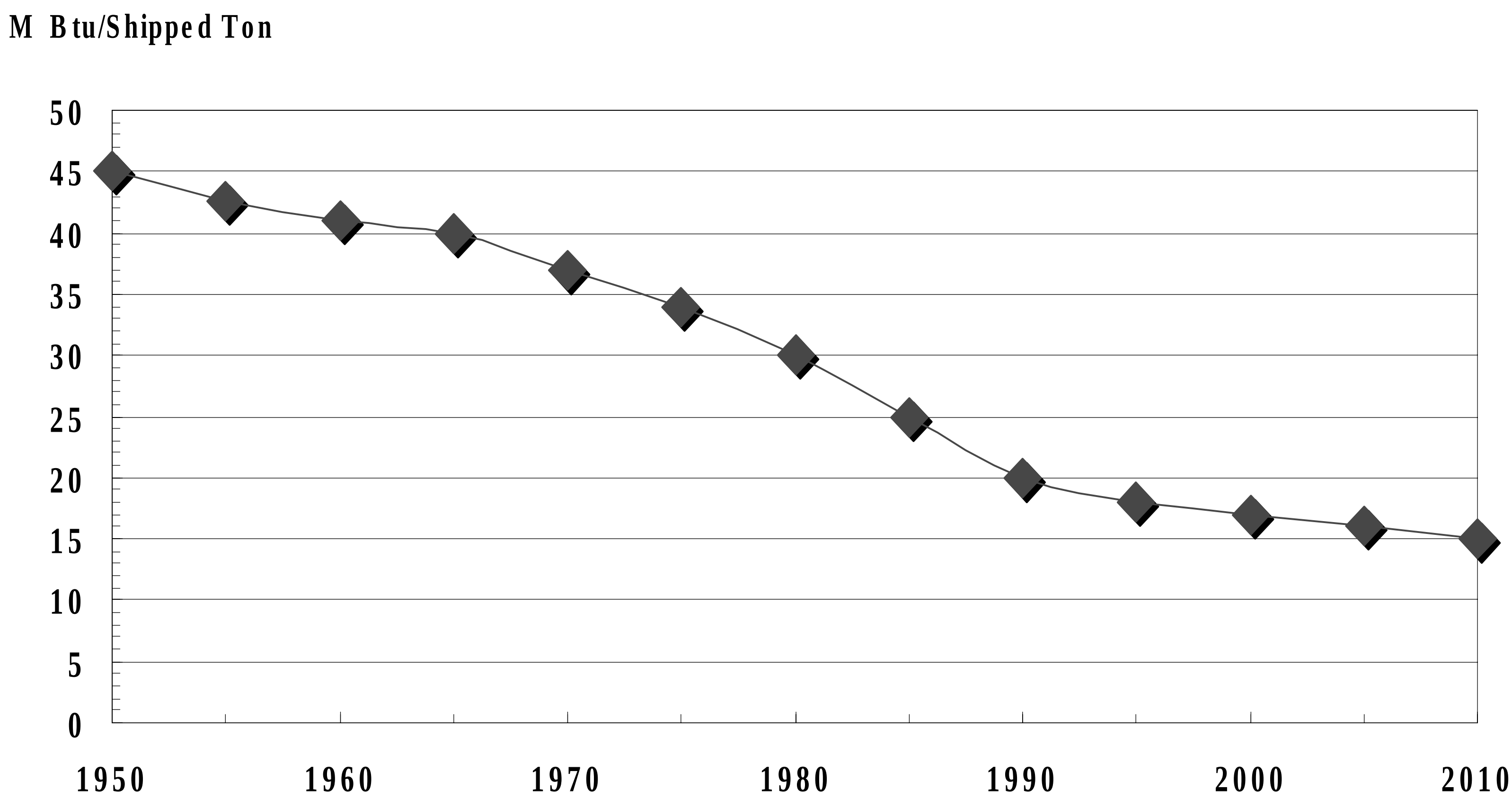

Figure 7. U.S. Blast Furnace Operations

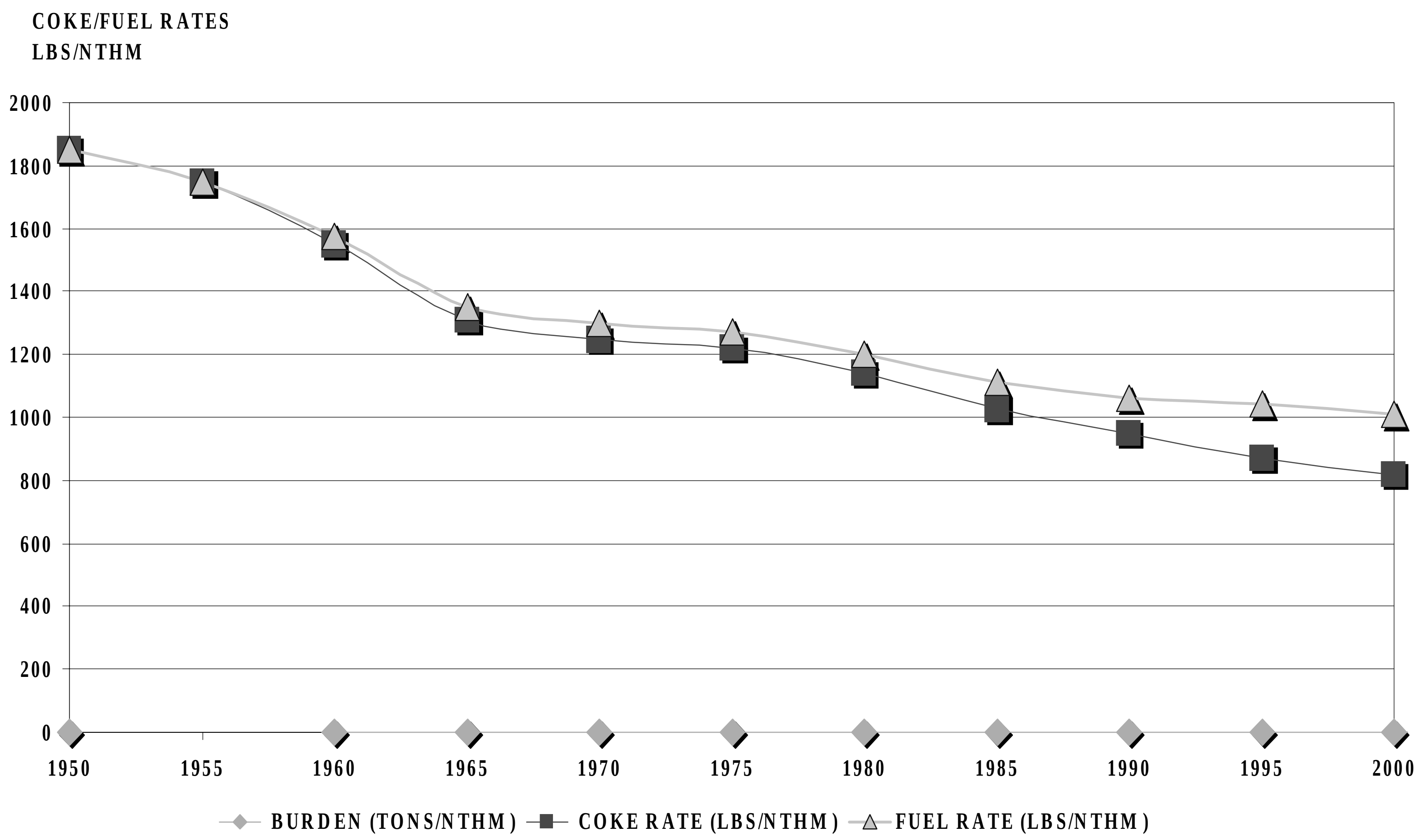

Figure 8. U.S. Steelmaking Processes

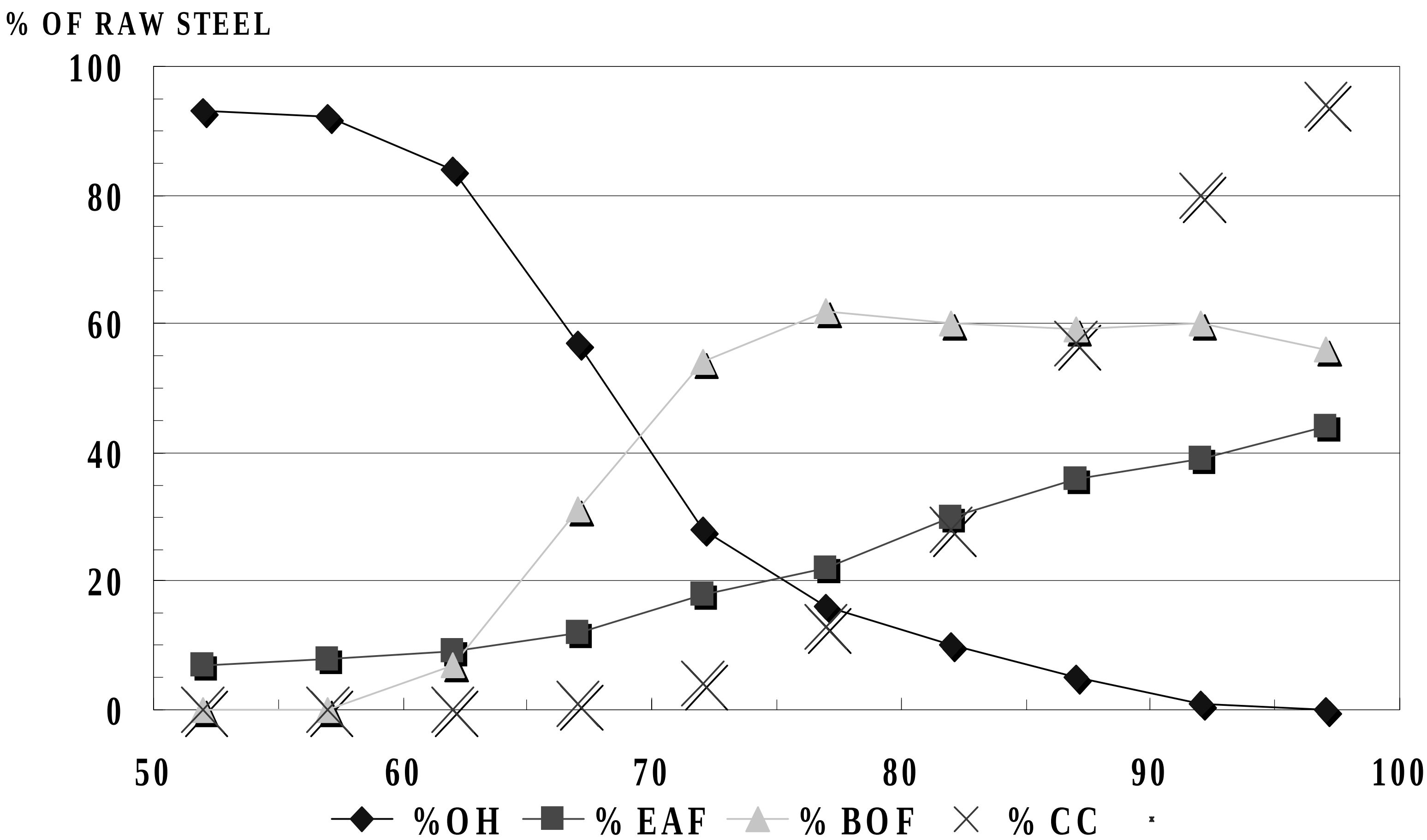

Figure 9. EAF Greenfield Mills: 1989-1999

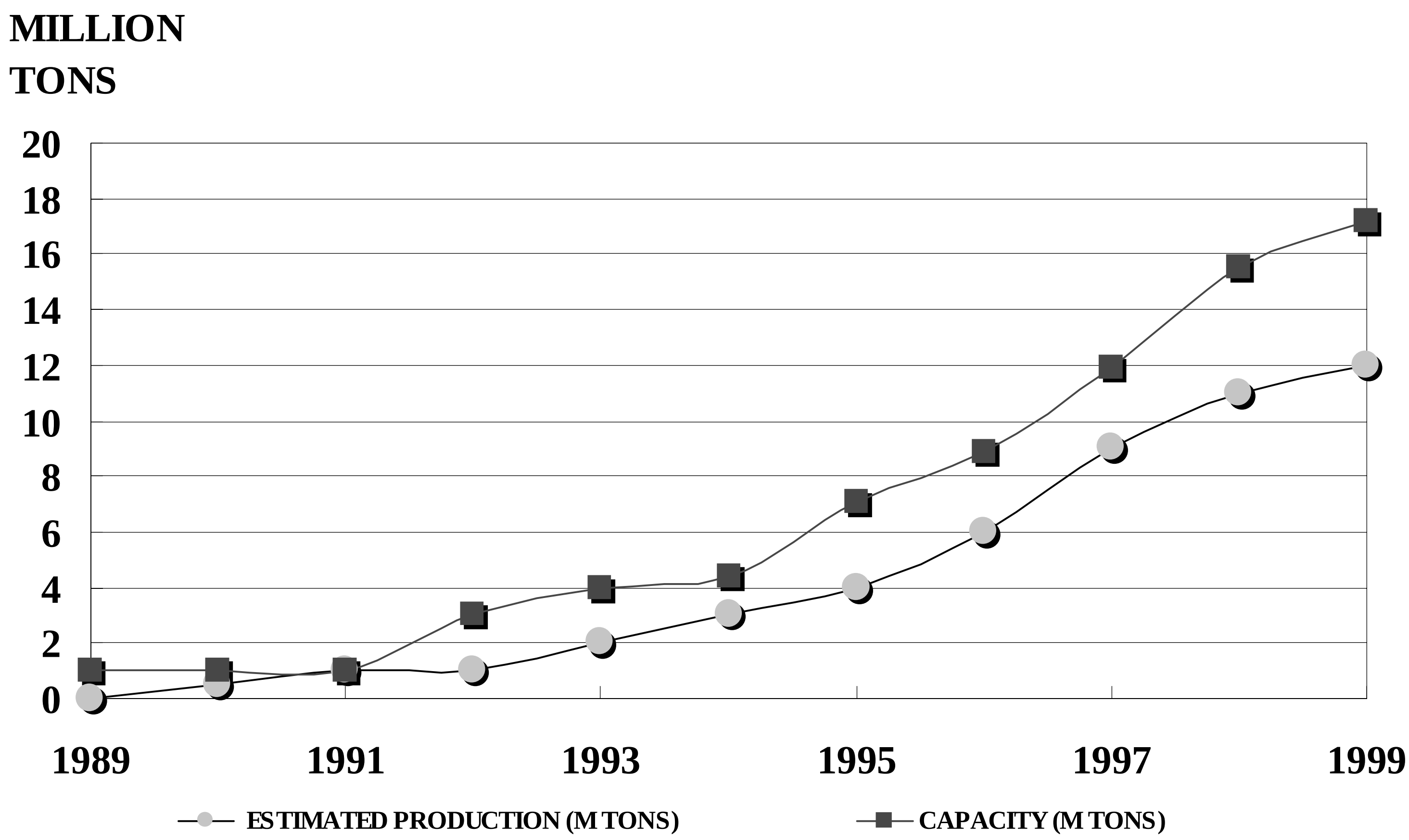

Figure 10. U.S. Scrap—Annualized Averages for #1 HMS

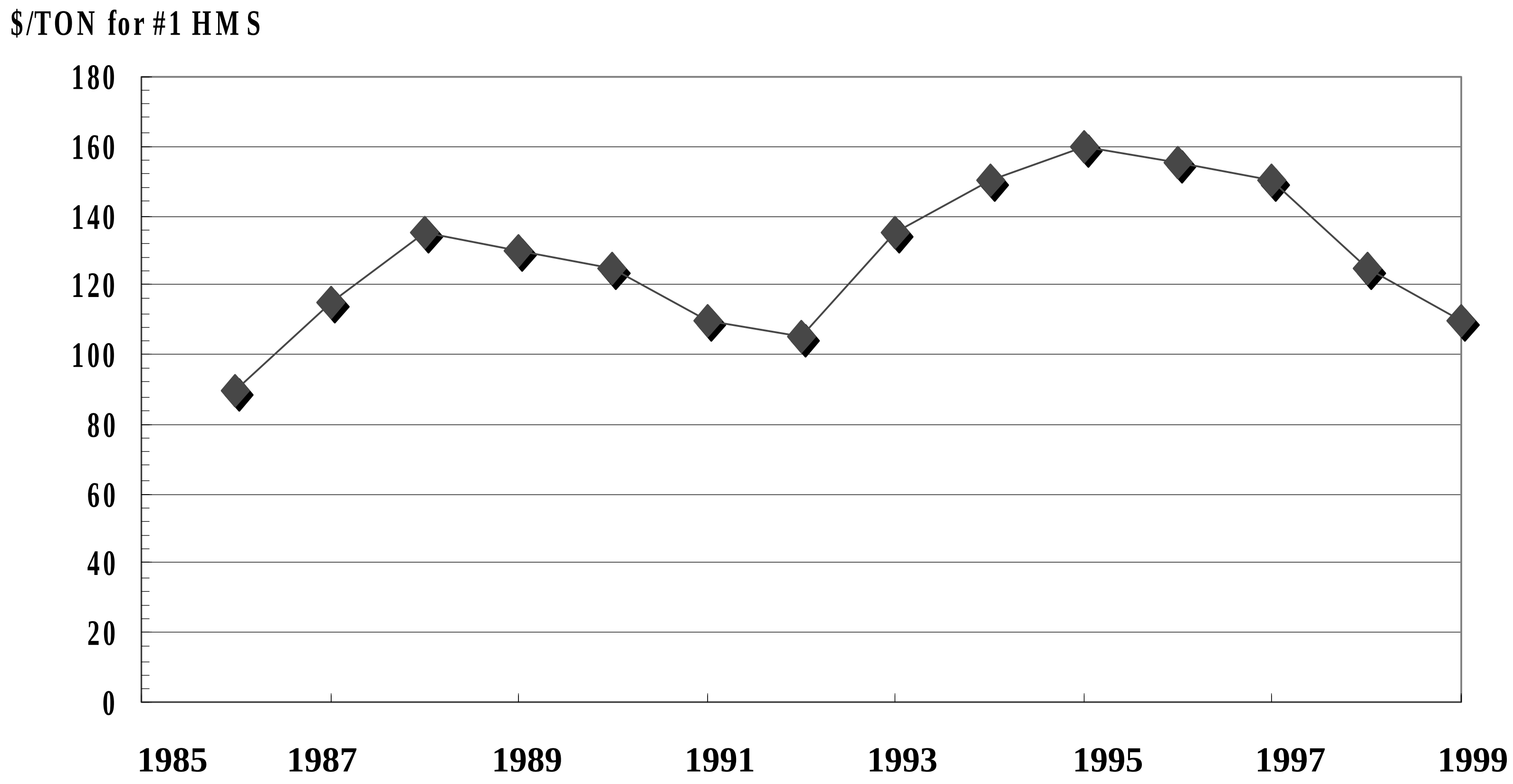

Figure 11. MiniMill 1998/1999 Tons vs Kwh
(769/T)

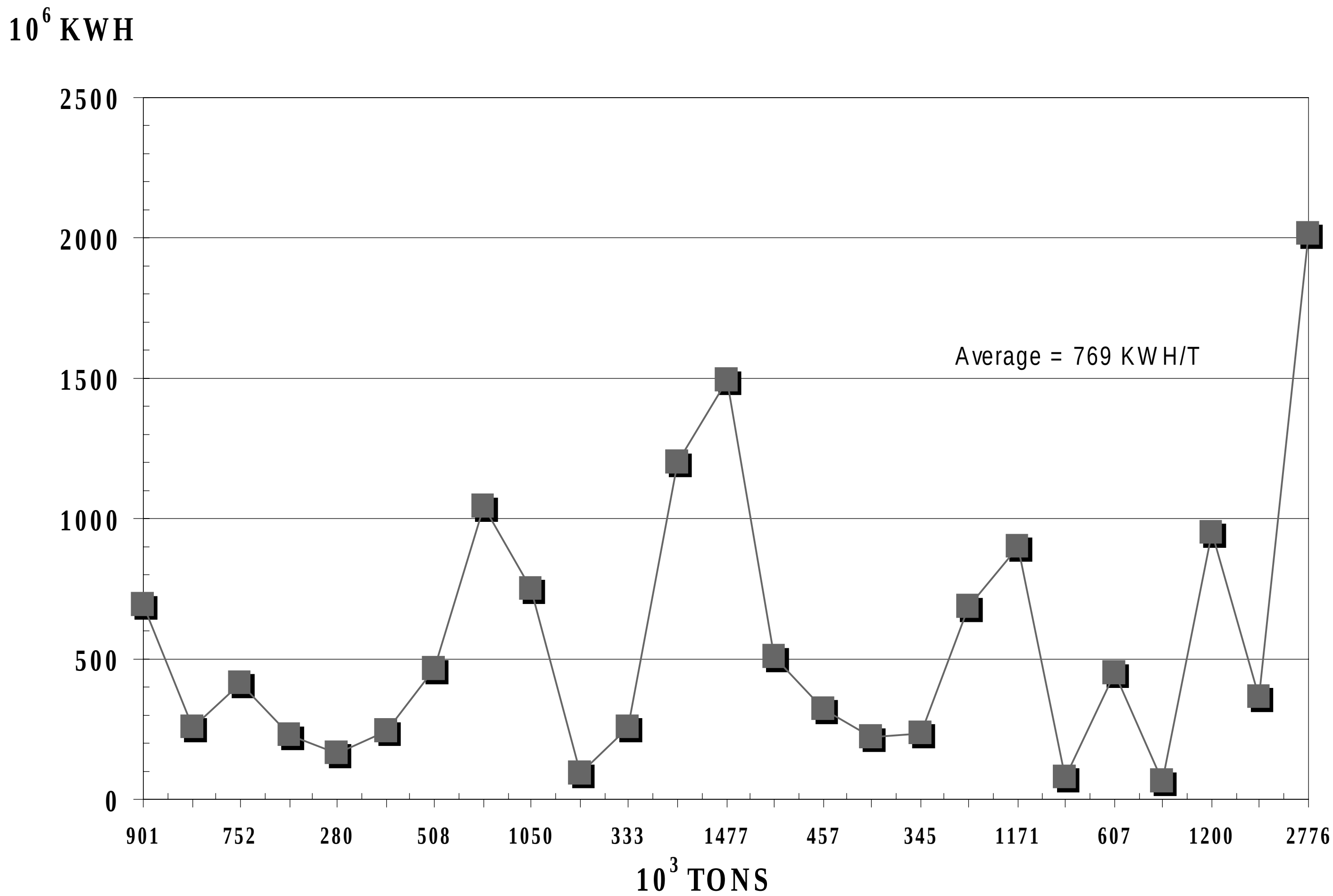

Figure 12. MiniMill 1998/99: Natural Gas vs Tons

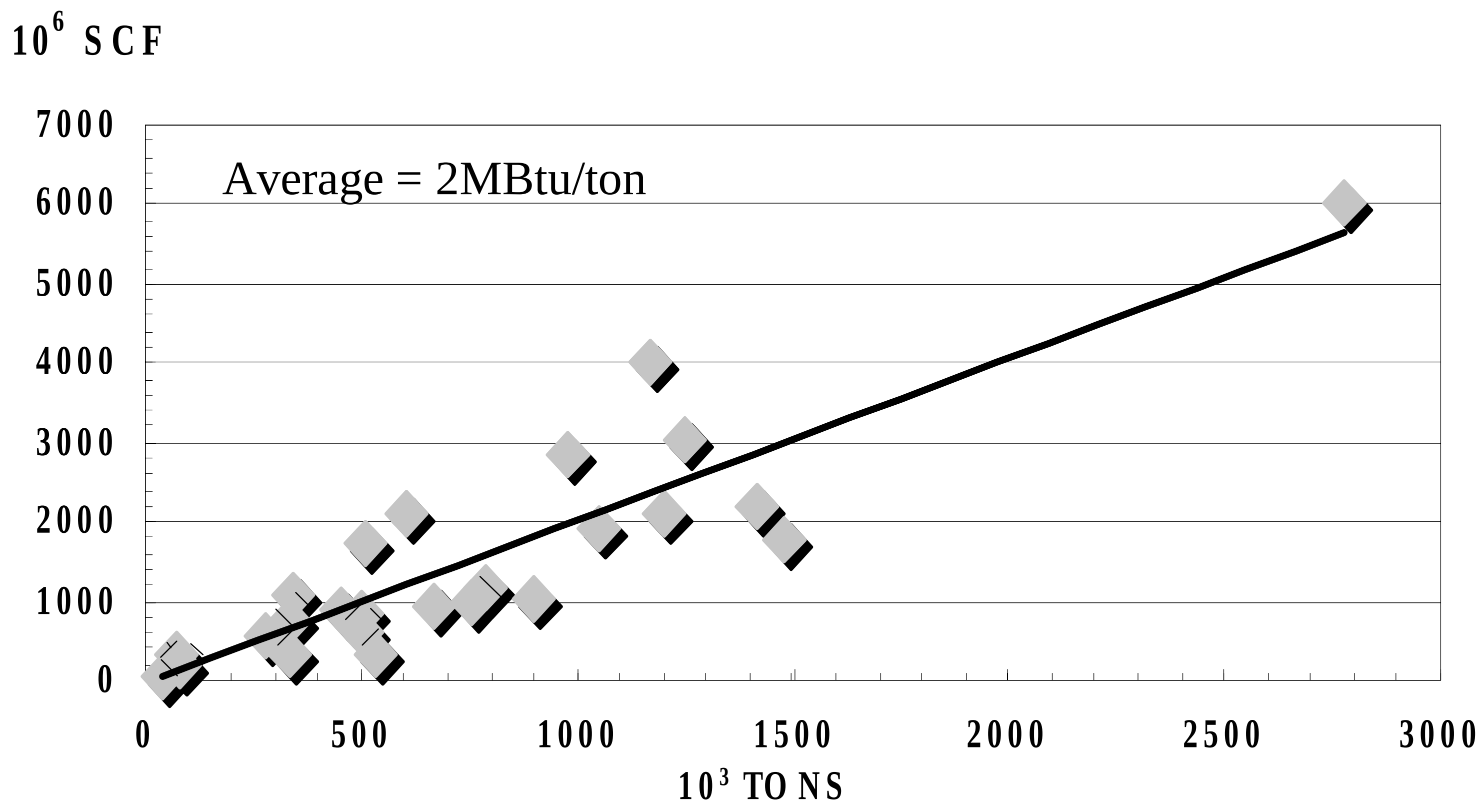

Figure 13. MiniMill 1998/99: Oxygen vs Tons

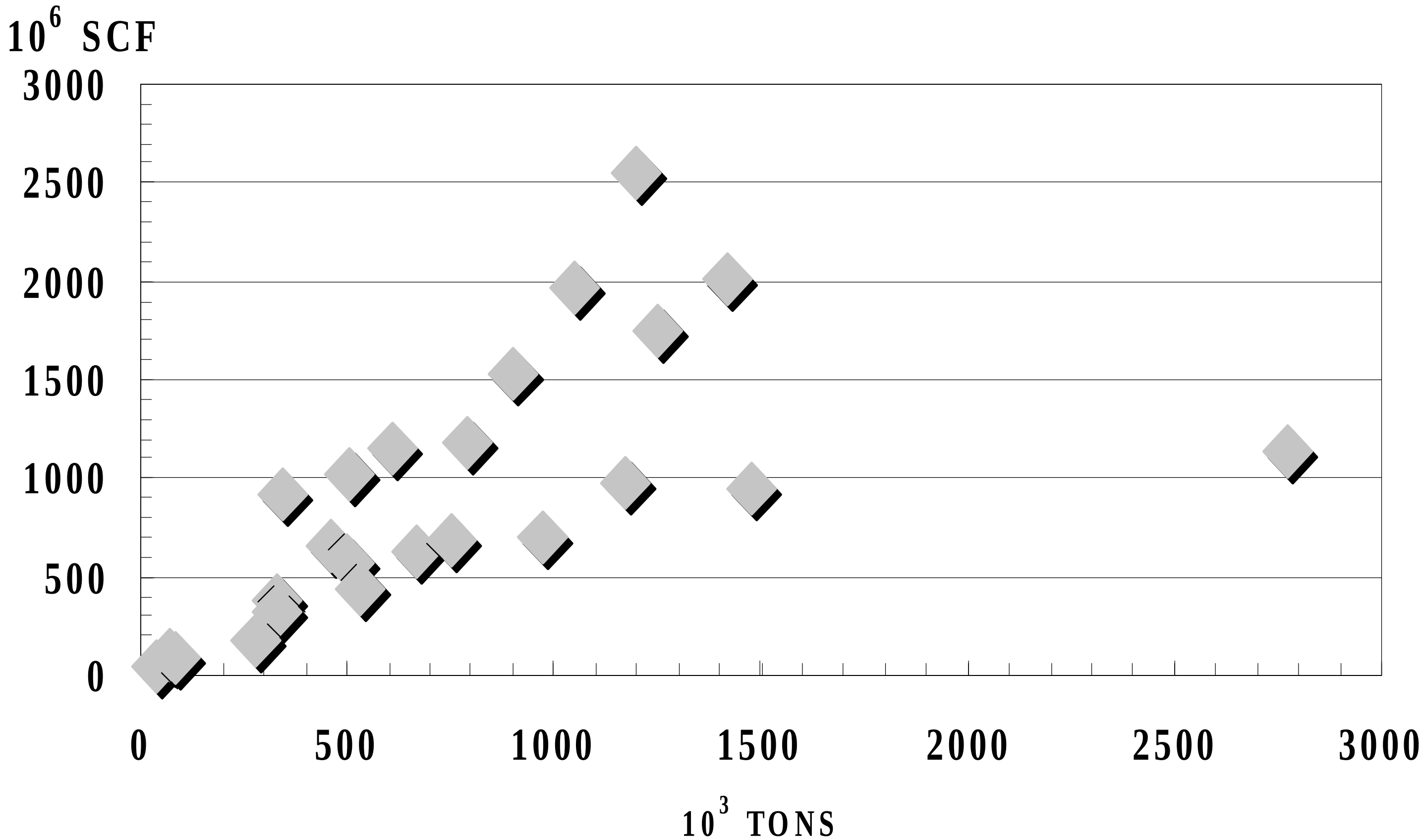

Figure 14. Carbon Equivalent (CE) Tons U.S. Steel Industry

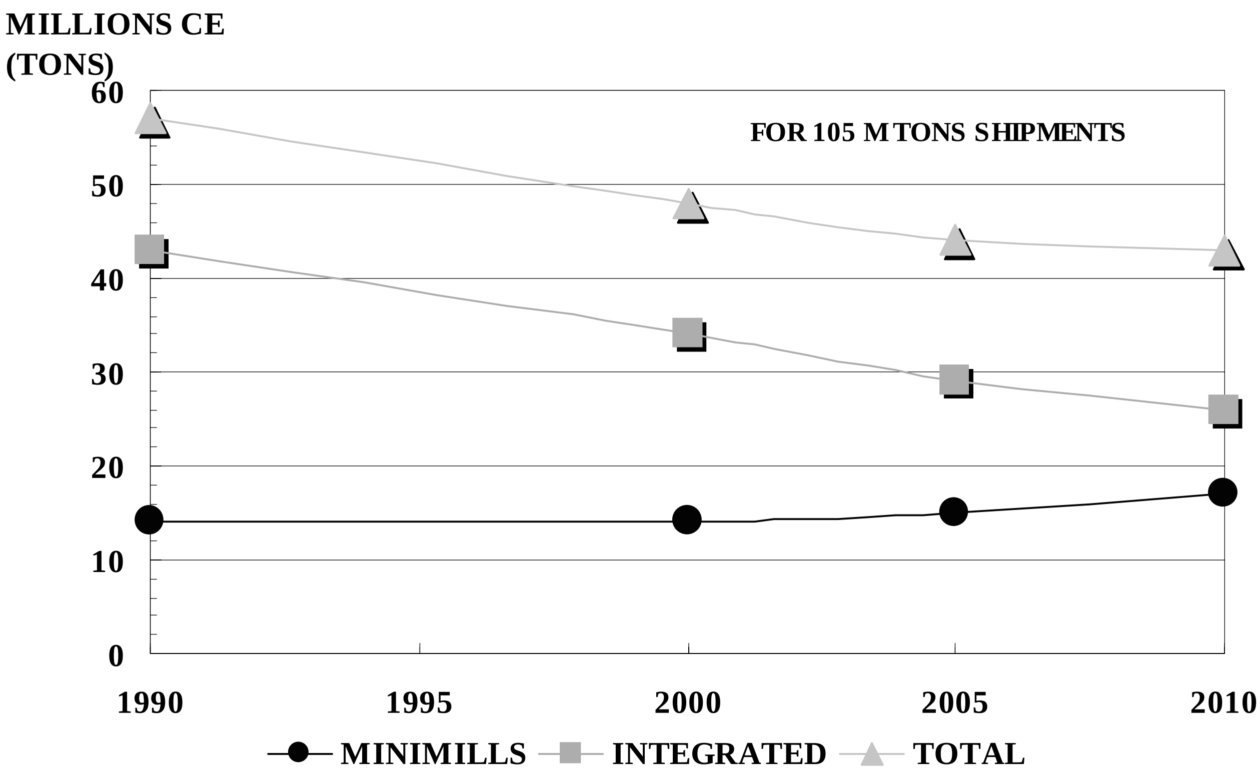

Figure 15. Carbon Equivalent (CE) Tons/Shipped Ton U.S. Steel Industry

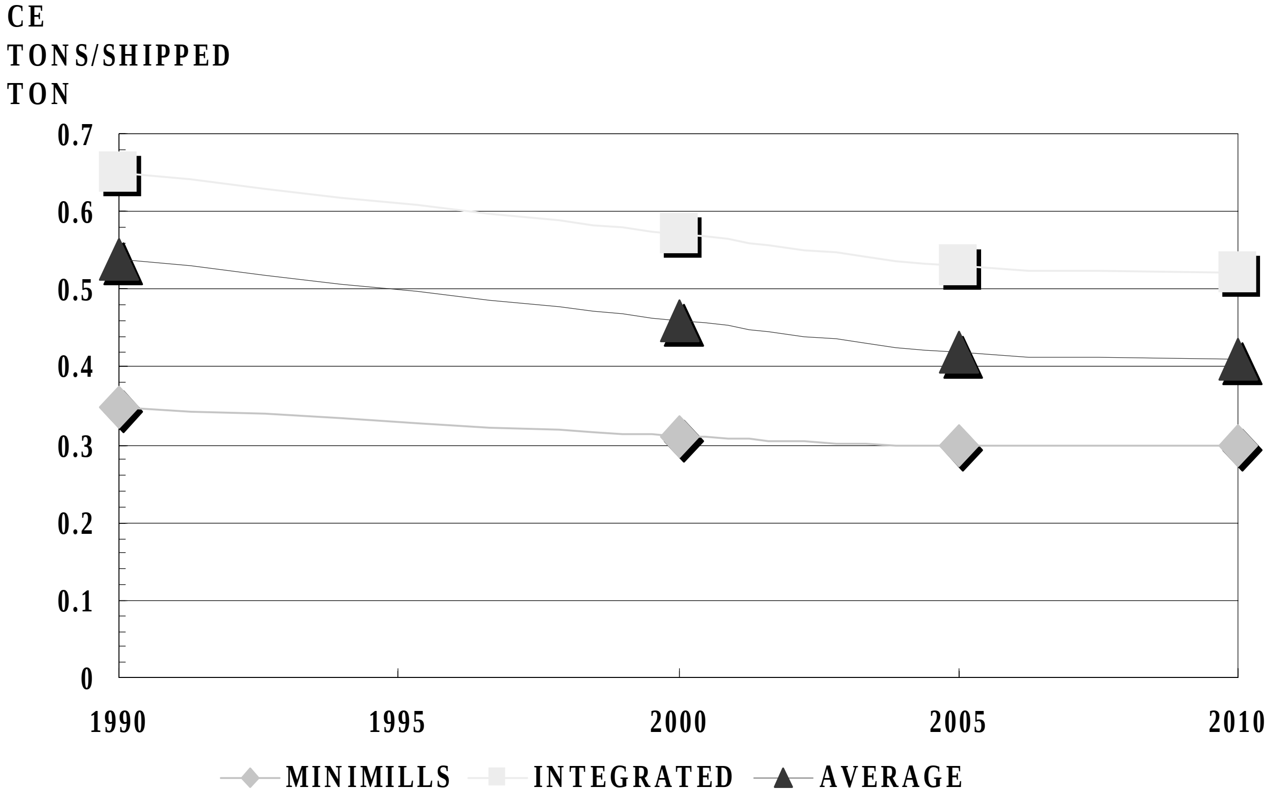

Figure 16. Annual CO_2 Emissions As C Equivalent